

**Thermochromic textiles and sunlight activating systems:
an alternative means to induce colour change**

Marie Ledendal, MA

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Heriot-Watt University
School of Textiles and Design
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Abstract

This thesis has investigated how the design process used by a textile printmaker practitioner requires further modification when the sun, uncontrollable by nature, is used to activate thermochromic leuco dyes, a dynamic surface variable. In the context of the use of the sun as the dynamic activator, the investigation is focussed on design applications of sun-screening textiles for both indoor and outdoor use. The work has been divided into two categories: the use of solar technology as a direct heater and as an indirect heat source using photovoltaic solar cells to power heat circuitry. The research has resulted in a set of recommended guidelines for textile printmaker practitioners for use when working with textile designs to create dynamic effects with thermochromic dyes, moving light and shadow imageries, in some cases utilising heat circuits activated using photovoltaics. The effect of the individual components of the design process is to allow creation of both dynamic imageries on the textile surface and ‘an extended imagery’, which at times may co-exist within two or three-dimensional space. This thesis, additionally, discusses the ability of the textile designer to achieve an intended aesthetic outcome, when working with an uncontrollable parameter, such as the sun, in comparison with the ‘traditional’ textile print design process.

Dedicated in loving memory of Johannes Angere,
a dedicated grandfather and researcher who will be forever loved

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"Methodology should not be a fixed track to a fixed destination, but a conversation about everything that could be made to happen."

(J. C. Jones, Design Methods, p.73, 1992)

List of abbreviations

AT – activation temperatures of the thermochromic leuco dyes

B – the colour blue within the NCS colour circle

B1 – the printed colour blue as defined within the thesis

B2 – the printed colour black as defined within the thesis

BG – the printed colour blue-green of the pre-defined colour palette as defined within the thesis

C – the chromaticness value within the NCS colour triangle

Cut-TX – samples that are laser cut, where T stands for test and X for the sample number

DB1 – the printed colour dark blue of the pre-defined colour palette as defined within the thesis

Devoré-TX – samples printed with devoré, where T stands for test and X for the sample number

DP – the printed colour dark purple of the pre-defined colour palette as defined within the thesis

Etch-TX – samples that are laser etched, where T stands for test and X for the sample number

Etch&Cut-TX – samples treated with both laser-etch and laser-cut, where T stands for test and X for the sample number

LB1 – the printed colour light blue of the pre-defined colour palette as defined within the thesis

LP – the printed colour light purple of the pre-defined colour palette as defined within the thesis

M – the printed colour magenta of the pre-defined colour palette as defined within the thesis

MG – the printed colour mint-green of the pre-defined colour palette as defined within the thesis

O – the printed colour orange of the pre-defined colour palette as defined within the thesis

Pigment-TX – samples printed with permanent pigments, where T stands for test and X for the sample number

p-v – polyester-viscose weave

R – the printed colour red as defined within the thesis

S – the blackness value within the NCS colour triangle

s.ch – silk chiffon

SHGC – solar heat gain coefficient

s-v.p – silk-viscose velvet

s-v.s – silk-viscose satin

t_1^{a-i} – the definition of the time interval it takes for the thermochromic dye to change colour from being active to inactive

t_1^{i-a} – the definition of the time interval it takes for the thermochromic dye to change colour from being inactive to active

t_2^a – the definition of the time interval that the thermochromic dye stay activated

t_2^i – the definition of the time interval that the thermochromic dye stay inactivated

TSET – total solar energy transmittance

Th.ch-TX – samples printed with thermochromic leuco dyes, some in combination with permanent pigments, where T stands for test and X for the sample number

W – the whiteness value within the NCS colour triangle

Y – the printed colour yellow of the pre-defined colour palette as defined within the thesis

List of publications and exhibitions

Ledendal, M., Christie, R. and Vettese Forster, S. (2013) ‘Thermochromic dyes and sunlight activating systems - An alternative means to induce colour change’, *AIC2013 Conference Proceedings*, July 9th to 12th, Newcastle upon Tyne, UK, 1, 193-196.

Jansen, B. and Ledendal, M. (2011) ‘Light and Shadow Play – The sun as an aesthetic trigger for urban textiles’, exhibition catalogue, *Ambience 11*, November 27th to 30th Pulsen Konferese, Borås, Sweden, 50-55.

Ledendal, M. (2014) ‘Butterfly Ink – textiles printed with thermochromic, heat sensitive, dyes, activated through sunlight’, *Formgalleriet 2014:01*, Galleri Elleroch, Malmö, Sweden, May 10th - June 12th.

Jansen, B. and Ledendal, M. (2011) Light and Shadow Play – The sun as an aesthetic trigger for urban textiles, *Ambience 11*, November 27th-30th, Pulsen Konferens, Borås, Sweden.

Chapter 1 Introduction

1.1 Justification for the project

This doctoral thesis focuses on using the sun to activate thermochromic (heat-activated colour-changing) dyes within textile applications. The main motivation for this research was that the author was critical towards the environmentally unsustainable ways used to activate thermochromic dyes in a majority of their applications. Until now, the main ways of heating the thermochromic dyes in textile design applications had involved the use of a variety of electrical heating mechanisms, as detailed in section 2.1.4, *Thermochromic dyes in design*. In contrast, in this thesis, the sole activator used is the sun, used directly (where sunlight is directly incident on the textile application) and indirectly (the sun is incident on photovoltaic solar cells in order to generate electricity that, in turn, activates the dyes). Prior to this thesis, the use of the sun as an activator, either directly or indirectly, in thermochromic textile applications had not been reported in the literature (see sections 2.1.4, 2.1.5 and 2.3.3). Therefore, the work in this thesis makes a contribution that is both new and necessary if more sustainable designs are to be conceived.

The intended target groups at which this thesis is aimed are established designers as well as design students who work with thermochromic dyes, either presently or in the future. Previously reported work with thermochromic dyes has primarily focused on creating and developing physical objects to investigate the potential of incorporating chromic dyes. Research has also been conducted on refining the use of electrical heating mechanisms involving heating solutions that use non-renewable energy sources. This conclusion has been drawn from analysis of the literature review in sections 2.1.4, *Thermochromic dyes in design*, and 2.1.5, *Heat sources to activate thermochromic dyes*. However, as discussed in section 2.2.1, *Design methods relevant to the use of thermochromic dyes and reversible dynamic patterns*, there was also a need identified for an extension of research discussing *how* to use the thermochromic materials.

Compared to more ‘traditional’ (non-dynamic) permanent pigments and dyes, thermochromic dyes present higher complexity both in terms of the nature of the actual physical printing process and the need to activate the dye to create colour change. The complexity of the material results in reduced control of the design outcomes, compared to non-dynamic designs. Therefore, the work in this thesis aimed to provide guidelines

to expand the aesthetic vocabulary for designers in order *to facilitate dealing with the complexity of the design process* when working with textiles using thermochromic leuco dyes. The findings of this work contribute specifically to this vocabulary when the dyes are activated using solar energy, since there was essentially no previous research in this area. A further contribution of this thesis is the development of a set of general guidelines for use when discussing and using thermochromic dyes. The intention was to achieve outcomes that facilitate and enhance the exploration and use of thermochromic dyes in design applications. The author, with many years of practical experience with thermochromic materials as well as prior work with healthcare environments (Ledendal, 2009), advocates the use of dynamic aesthetics and colours to create stimuli that might lead to enhanced well-being. The following possible application areas are proposed: interior products for healthcare, homes for the elderly, environments for children, multisensory rooms, offices and urban space. Two potential applications explored specifically in this thesis are sun-screening textiles for both indoor and outdoor settings. These two specific applications, as described in chapter 6, section 6.3, have been used as examples to discuss the future feasibility of these types of design applications when the activator for the thermochromic dye is powered by photovoltaics. In addition, outdoor sunscreens have been used, as described in chapter 5, section 5.6, as examples to incorporate findings based on three-dimensional imagery, derived from light and shadows, into a particular context.

1.1.1 Approach

The practice-based research in this thesis was carried out with a design approach, primarily using the research methods that apply specifically to the creative industries. The author's prior tacit artistic and print design related knowledge provided the foundation for her to adopt the role of both the researcher and the textile printmaker practitioner through *participatory research*. Using a design brief, a conceptual framework to accommodate the use of chromic dyes was constructed, to be used as a comparative analytical tool, thus extending the established traditional 'general' design process. The framework was devised to evaluate the findings of the design process, carried out in the role of the textile printmaker practitioner. The body of work is largely subjective in nature, on the basis of the participatory research approach. Therefore, *reflexivity* was also used throughout as a complementary analysis method in order to allow reflection on the author's subjective role within the observations and how this

shaped the outcomes of the research. The work, primarily built on an extensive set of observations, as described in section 3.7 *Observation methods*, was analysed and formulations developed from this design approach. However, in certain specific situations, the author chose to reinforce the findings of certain lines of enquiry using a scientific, often quantitative, approach. In this way, the subjective nature of the participatory research, was cross-referenced using results from an objective point of view. Specific areas of the research demanded a more intense scientific (quantitative) approach for example, the collaborative work described in chapter 6 on the development of systems using photovoltaics as a means for indirect activation of the thermochromic dye.

1.2 Research Aims and Objectives

The principal aim of the research described in this thesis was to provide guidelines that expand the *aesthetic vocabulary* to aid designers in the complex design process when working with textiles using thermochromic leuco dyes, specifically when utilizing the sun as a more sustainable, alternative means to activate such dyes. The objectives were as follows.

- To expand the aesthetic vocabulary for textile printmaker practitioners', when the sun acts as a *direct activator* of sun-screening textiles printed with thermochromic leuco dyes.
- To expand the aesthetic vocabulary for textile printmaker practitioner, when the sun acts as an *indirect activator* of sun-screening textiles printed with thermochromic leuco dyes.

1.3 Research Questions

- Q1 What will be the effects of the low-technology solution of direct solar activation, in the context of the aesthetic vocabulary for the area of textile print design, when thermochromic leuco dyes are used to create printed imageries on sun-screening textiles?
- Q2 Is it possible to use the sun as an indirect activator, using a high-technology solution involving solar cells to power electrical heating mechanisms that in turn activate textiles printed with thermochromic leuco dyes?
- Q3 What are the differences, from a textile printmaker practitioner's perspective, between using the sun to activate the thermochromic leuco dyes for:

- (a) direct activation compared to using ‘traditional’ electrical heating mechanisms or body heat;
 - (b) indirect activation compared to using direct solar activation or ‘traditional’ electrical heating mechanisms?
- Q4 Which possibilities in the development of the research on the integration of photovoltaics into textiles can be predicted, from a design perspective, concerning future applications using textiles printed with thermochromic leuco dyes?
- Q5 How can the sunlight, used to activate thermochromic leuco dyes that are printed on sun-screening textiles, also be utilised in combination with surface treatments (devoré print and/or laser treatment) to create additional aesthetic qualities and effects within a space?
- Q6 Do such additional qualities and effects (as might be identified in answering in Q5) provide a similar or different dynamic behaviour as compared with sun-activated thermochromic leuco dyes, established from the context of descriptors for ‘reversible dynamic patterns’?

1.4 Structure of the thesis

The thesis is divided into seven chapters. This introductory chapter, chapter 1, presents the purpose of the thesis and describes the layout of the content.

Chapter 2, *Literature Review*, describes and analyses relevant previously reported work relating to thermochromic dyes (sections 2.1.4, 2.1.5 and 2.2.1) as well as the use of photovoltaics that are integrated into textiles (section 2.3.3). Chapter 2 includes examples of products and/or prototypes, illustrated where appropriate, relating to design with thermochromic dyes, with particular emphasis on the most prominent designers, such as Orth, XS Labs, Worbin and Berzina, as well as a description of the design methods used, and also of Philips Design when discussing photovoltaics used within textiles. However, in addition, the scope of the review has been extended, to place the findings of this study into context. Chapter 2 thus also includes a general overview of selected topics that are important within the thesis (thermochromic dyes, design methodology, sun-screening, photovoltaics, as well as the principles of shadow formation) aimed to allow the reader to understand the wider context of the discussions presented throughout this thesis. The order of presentation of the information in chapter

2 (thermochromic dyes, design methodology, sun-screening and photovoltaics and finally principles of shadows) reflects the relative importance of the individual topics in relation to the overall research. For example, most information from chapter 2 feeds into more than one of the experimental chapters (chapters 4-6), while section 2.4, *The principles of shadows*, is only relevant to chapter 5.

Chapter 3, *Methodology*, provides a thorough presentation of the methods used within this thesis. This includes an overview of the methods used (section 3.1), more detailed descriptions of specific methods and descriptions of the terminology, materials and technologies used. Frequent reference is made to this extensive methodology chapter within the experimental chapters (4-6), as well as at times in the concluding chapter (7), aiming to minimise repetition within these chapters. However, selected repetition of certain information and/or figures presented in chapter 3 is at times used in chapters 4-7, in the interests of clarity.

The reader will find the experimental body of work divided into three parts, covering chapters 4 to 6:

- Part I – investigation and formulation of the relationship between thermochromic dyes and direct solar energy, in terms of activating and deactivating the dye. (Presented in chapter 4)
- Part II – the investigations are divided into two groups: The first (part IIa) focuses on the dynamic aesthetics created by the use of laser technology and/or devoré print used in combination with the colour change created by thermochromic dyes activated by sunlight. The second (part IIb) is an in-depth study of the potential to design several surfaces (e.g., textiles, light and shadows) within a three-dimensional space, defined in section 5.8 as ‘the extended imagery’. This imagery is created by the interplay between sunlight and a textile when solar energy is used as an activator for thermochromic dyes in specific situations. (Presented in chapter 5)
- Part III – investigates the untapped potential in using photovoltaics to power heating mechanisms that in turn activate thermochromic dyes (indirect solar energy). (Presented in chapter 6)

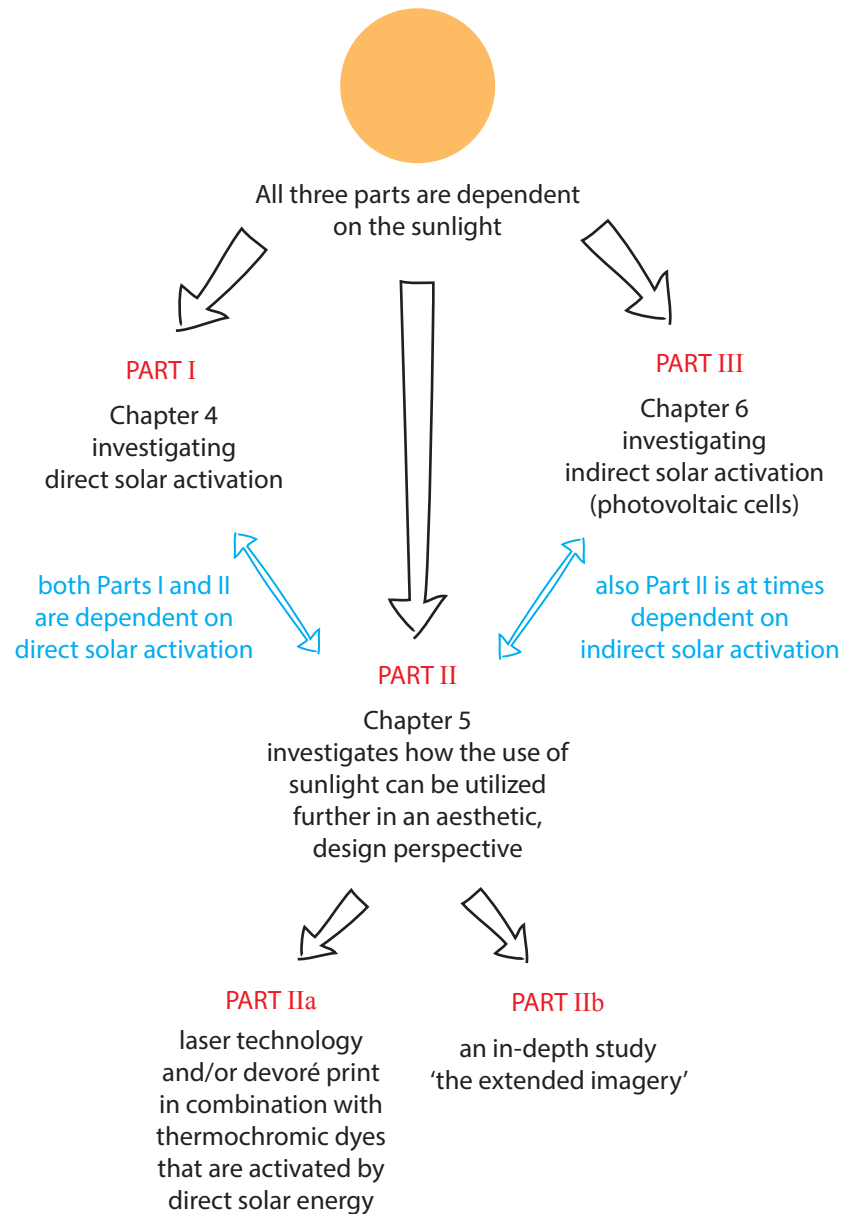


Diagram 1.1 Illustration of the three parts of experimental work, and how they are connected.

The common denominator of the three partly self-standing experimental investigations is their use of solar energy (see Diagram 1.1). Parts I and III represent two different ways of utilising solar energy. Part I (chapter 4) employs a low-technology heating mechanism, using the heat of the sun to directly activate the thermochromic dyes (referred to throughout the thesis as direct solar energy or a direct activator). Part III (chapter 6) uses a high technology mechanism where solar energy is harvested through photovoltaics to power heating mechanisms that in turn activate the thermochromic dyes (referred to throughout the thesis as indirect solar energy or an indirect activator). It was considered important to investigate the design potential of both methods of using

solar energy aiming to enhance the environmental features in designs that involve activating thermochromic dyes. Activation using the low technology alternative was regarded as an approach that minimises the use of electronics, and further provides a more sustainable and a simpler and thus potentially more recyclable product. A high technology solution using electrical energy from photovoltaics was considered aiming to provide a more sustainable source of energy when electronics are used, compared to previously used design concepts.

The investigations described in part II (chapter 5) feed into the other parts because ‘the extended imagery’ as well as the possibilities of additional dynamic effects on the surface of the textile are by-products of the use of solar energy (indirect and/or direct) as an activator for the thermochromic dyes. In part IIa, the dynamic aesthetics using the low-technology direct heating approach were explored. This simple method of heating the thermochromic dye provides a more environmentally friendly solution compared to traditional incorporated electrical heating mechanisms. Further, the aesthetic extension into three dimensions described in part IIb, due to the presence of incident light, is not applicable for other activators. Subsequently, it was found that using solar energy as an activator for the dyes, requires a significantly modified design process compared to using established activators (see section 2.1.5). The studies in part IIb underline the widening of the design vocabulary that the use of sunlight evokes: the possibility of designing at several levels (defined in section 5.8 as ‘the sun-screening textile’, ‘the intermediate zone’ and ‘the incident surfaces’) within three-dimensional space in relation to the more ‘traditional’ two-dimensional textile surface. Part II is more closely linked with part I, following directly from the investigations and findings of part I. This is not only because part IIa provides the basis for an extension of dynamic effects created through direct solar activation, but also because the use of direct sunlight automatically creates the opportunity for an extended imagery (part IIb). In part III, the possibility to produce extended imagery depends on the placement of the photovoltaics. The designer obtains the possibility of designing an extended imagery if the photovoltaics are integrated within the textile product.

Chapter 7, *Conclusions*, links the findings of chapter 4-6. The purpose of the work in this thesis aimed to provide guidelines to expand the aesthetic vocabulary for designers to facilitate dealing with the complexity of the design process when working with textiles using thermochromic leuco dye with the intention that the findings will

strengthen and facilitate the exploration and use of thermochromic dyes in design applications. To this end, the discussion in chapter 7 compares the relatively straightforward textile design process using non-thermochromic dyes to the increased complexity of the textile design process using thermochromic dyes. Compared with using traditional heating mechanisms, which only provides a two-dimensional aesthetic, using sunlight as an activator provides the opportunity to create a three-dimensional aesthetic – the extended imagery. The different design processes described in chapter 7 are illustrated by four schematic diagrams (I-IV). The schematic diagrams describe the level of controllability (assessed as ‘controllable’, ‘partly controllable’ or ‘uncontrollable’) at different stages of the design process. The analysis demonstrates the increase in complexity, as well as where in the design process this occurs, not only using dynamic dyes but also textiles back-illuminated by sunlight. Section 7.1.3 presents findings in the form of for example the sets of guidelines derived from the outcomes of chapters 4-6 that are applicable for designers working with thermochromic dyes to increase (when possible) the level of control of the aesthetic outcome.

Chapter 7 also assesses the extent to which the thesis presents a more sustainable solution for activating thermochromic dyes, compared to previously described methods, as well as possible ideas for future research.

1.4.1 Summary of Chapter 4

In chapter 4, *The sun as a direct activator for sun-screening textiles printed with thermochromic leuco dyes*, an investigation is described of the relationship between thermochromic dyes and direct solar energy, leading to activation and deactivation of the dye (part I). These investigations were conducted using the low-technology direct activation mechanism; either by heat derived from the rays of the sun, or a glass window heated by the sun, or both. In both cases, activation is affected by the ambient temperature. The investigations in chapter 4 aimed to answer the question as to whether using direct solar activation to activate thermochromic dyes would need a different approach to the design process, in relation to other previously used activation methods. The investigations in the chapter demonstrate the difficulty in controlling the aesthetic outcome of the printed thermochromic designs in working with a highly uncontrollable parameter such as direct solar activation.

The main contributions to knowledge in chapter 4 are sets of ‘guidelines’ in the form of ‘design variables’, defined by the author, to expand the aesthetic vocabulary for designers using thermochromic leuco dyes, as well as amendments to descriptors for the ‘reversible dynamic pattern’, as used in previous research (see 2.2.1). This chapter presents two different levels of design variables as well as amendments to the descriptors: one level concerning activation of the thermochromic dye in general and the other specifically concerning direct solar activation.

Additionally, chapter 4 discusses the theory of mixing thermochromic dyes. Section 4.1.1 presents a set of graphics, defined by the author, supported by explanations of the mixing principles for thermochromic leuco dyes, both purely with leuco dyes as well as combined with permanent pigments, thus providing practical guidelines for the designer.

1.4.2 Summary of Chapter 5

In chapter 5, *Utilizing sunlight to create added aesthetic qualities, due to light translucency within the substrate materials*, the reader will find that the investigations are divided into two groups: One focuses on the dynamic aesthetics created by the use of laser technology and/or devoré print in combination with the colour change created by thermochromic dyes activated by sunlight (part IIa). The other is an in-depth study of the potential for designing at several levels within a three-dimensional space, created due to the interaction between sunlight and a textile when solar energy is used as an activator for thermochromic dyes (part IIb). The main contributions of the investigations of part IIa are utilising layering of laser technology treatments on thermochromic prints to create dynamic effects in which not only the colour but also the imagery undergo change (section 5.4.4). The main contributions from part IIb, in section 5.8, involve the construction of the, ‘extended imagery’, through levels defined by the author as ‘the textile surface’, ‘the intermediate zone’ and ‘the incident surfaces’, and a set of key variables relating to these levels (sections 5.6.2 and 5.7).

1.4.3 Summary of Chapter 6

In chapter 6, *The sun as an indirect activator for textiles printed with thermochromic dyes*, the reader will find an investigation of the potential to use energy harvested by photovoltaics to power heating mechanisms that in turn activate thermochromic dyes (indirect solar energy). Additionally, there is an investigation of the relationship

between thermochromic dyes and indirect solar energy, during activation and deactivation of the dye. These investigations (part III) are conducted using high-technology heating mechanisms, based on systems constructed using both flexible and rigid photovoltaics, as well as glass wafers containing parallel connected electrical microheaters, developed specifically for the investigation using state of the art technology. The high-technology solution using electrical energy from photovoltaics was investigated as another possibility to provide a more sustainable energy source for activation, compared to published design concepts where electronics are used, for example by Orth and International Fashion Machines, XS Labs, Worbin and Berzina, examples of which have been provided in section 2.1.4, *Thermochromic dyes in design*.

The main contribution in chapter 6 is the proof of the concept that photovoltaics may be used successfully as an energy source to power the heaters to activate thermochromic dyes within textiles (section 6.1). Further, the chapter presents additional contributions to the meaning and use of the ‘design variables’ as defined chapter 4 (‘amount of thermal energy’, ‘heating ability’, ‘time interval/temporal pattern’ and ‘distribution of heat’). This chapter also adds to the descriptors for ‘reversible dynamic patterns’ when using the sun as an indirect heater, compared to two activation applications, direct solar activation and ‘traditional’ heat circuitry (section 6.2). Additionally, chapter 6 discusses future scenarios for the use of integrated photovoltaic cells in textile applications (section 6.3).

1.5 Limitations

- Activation temperatures of the thermochromic leuco dyes used within this study varied within a temperature range of 20-47°C. Due consideration was given to the chosen activator (the sun) as well as the environments used in the investigation (carried out in the areas of the Scottish Borders, UK, Copenhagen, Denmark and the Scania region (Skåne), Sweden). The lower temperature threshold dyes were chosen taking into account the anticipated average ambient temperatures of the environments investigated, in the range 20-25°C (outdoors during summer months, when the sun is at its strongest, and the need for sun-screening is the highest, as well as indoors all year around). Dyes with an activation temperature lower than 20°C were not considered because they would be permanently activated in this temperature range in and the activator (the sun) would not have an impact. Dyes with the higher temperature threshold (47°C)

were chosen for situations where additional heat would be required to initiate change, more than would be likely to be experienced within the chosen environments of investigation.

- The thermochromic leuco dyes selected for use within in the research were, due to cost considerations, ‘off the shelf’ products with a standard set of activation temperatures and colours. Non-standard dyes with custom-made activation temperatures as well as hues are significantly more expensive. However, this limitation was judged not to have impacted significantly on the research outcomes, since the standard dyes provided a reasonable range of colours suitable for the intended application, within the required activation temperature span.

Chapter 2 Literature Review

The information and data presented in this chapter are provided as background towards achieving the goal of this thesis: to utilize sunlight (directly and indirectly) to induce colour change through activation of thermochromic dyes that are printed onto sun-screening textiles. This chapter includes examples of products and/or prototypes, illustrated where appropriate, relating to design with thermochromic dyes, with particular emphasis on the most prominent designers, such as Orth, XS Labs, Worbin and Berzina, as well as a description of the design methods used, and also of Philips Design when discussing photovoltaics used within textiles. However, in addition, the scope of the review has been extended, to place the findings of this study into context. This chapter thus also includes a general overview of selected topics that are important within the thesis (thermochromic dyes, design methodology, sun-screening, photovoltaics, as well as the principles of shadow formation) aimed to allow the reader to understand the wider context of the discussions presented throughout this thesis. The order of presentation of the information in this chapter reflects the relative importance of the individual topics in relation to the overall research. For example, most information from the literature review feeds into more than one of the experimental chapters (chapters 4-6), while section 2.4, *The principles of shadows*, is only relevant to chapter 5.

2.1 An introduction to thermochromic dyes

This thesis investigates the ability to heat thermochromic dyes using sunlight, both directly and indirectly, as stated in the aim of the research in section 1.2. Thermochromic dyes can, due to their ability to react to thermal stimuli, be defined as ‘smart materials’. A ‘smart material’ in this thesis refers to materials that, as defined by Tao (2001), have the ability to react to an input and then produce an output in response. (Tao, 2001, pp.2-3) The thermochromic material, one of a number of chromic materials (for example photochromic, electrochromic, piezochromic and hydrochromic), provides visual output through its colour change when subjected to an environmental input. In the case of thermochromic this involves variations in temperature. These colour changes may be both controllable and reversible. (Christie, Robertson and Taylor, 2007, p.1; Seymour, 2008, pp.17-18; Christie, 2013, pp.4-6) Smart materials have been explored and developed in different ways, in combination with textiles, to create a variety of ‘smart textiles’ that can react, interact and respond. These are textiles that, through added value, display a new set of functional as well as artistic values, in contrast to ‘traditional’

textiles. Smart textiles as defined by Tao (2001) are sub-divided into two categories; *active* and *passive*. Thermochromic dyes fall into the latter category, whereby a material *reacts* through a change (such as colour change) towards stimuli in its environment. An active smart textile has the ability, in addition to the change in physical appearance, to *act* on the stimuli and provide information that allows a response (for example by electrical impulses). (Tao, 2001; Braddock Clarke and O'Mahony, 2005; Bonnemaïson and Macy, 2007; Seymoure, 2008,) Materials that do not demonstrate the ability to react towards stimuli are termed 'traditional textiles' in this thesis.

2.1.1 Thermochromic dyes

Thermochromic dyes are divided into two groups: thermochromic leuco dyes (also referred to, within this thesis, as simply thermochromics or leuco dyes) and thermochromic liquid crystals (occasionally referred to, within this thesis, as liquid crystals). This chapter primarily discusses the leuco dye types and only outlines liquid crystals, reflecting the focus within this thesis on leuco dyes. Thermochromic materials on the market are at present mostly used for applications such as strip thermometers, measuring body temperature in medical applications, food packaging or tests of electronic circuitry. (Christie, Robertson and Taylor, 2007, p.1)

The thermochromic leuco dye changes from coloured to colourless on heating. When the dye is in its activated state it is no longer optically visible. (Christie, 2013, pp.6-7) Some leuco dyes can exhibit a slight, light hue after complete activation, whereas others, visually, become completely colourless. (Kooroshnia, 2013b) Mixing the leuco dye with permanent pigments can create a visual colour change from one colour to another. The leuco dye is microencapsulated, meaning that the chromic system is protected within an encapsulating wall structure. The dye consists of a three-part system; the leuco dye, an acid activator (a developer) and a low melting solvent. The solvent melts to a liquid when the material is heated, which allows a chemical reaction between the three ingredients leading to loss of colour. The solvent re-solidifies on cooling and the reaction between the three components reverses, thus regenerating the colour. (Christie, Robertson and Taylor, 2007, p.2; Christie, 2013, pp.6-14) The microencapsulated dye particles within thermochromic leuco dyes are at least 10 times larger than typical ink pigment particles. The main manufacturers of thermochromic dyes are Matsui (Japan) and LCR Hallcrest (UK). The latter has acquired the former Colour Change Corporation (USA). (Christie, 2013, p.13) The dyes can be supplied

either mixed into a slurry base or as a powder depending on which properties are needed for the desired purpose (e.g., printing, dyeing or yarn extrusion). (LCR Hallcrest, n.d. and Matsui, n.d.)

Leuco dyes can be provided with several activation temperatures, which is the temperature at which most of the dye has initiated a colour change. In theory, dyes with any activation temperatures within a certain temperature range (-10°C up to about $+69^{\circ}\text{C}$) are capable of being produced (the temperature range differs slightly between suppliers). However, the number of varieties that are on the market is more limited. LCR Hallcrest supplies dyes with activation temperatures of 15°C , 31°C and 47°C . Matsui supplies dyes with nine different activation temperatures between 12°C and 41°C (Type 5 to Type 37). The visual colour change of the dyes supplied by LCR Hallcrest is reported to start at around 4°C below the stated activation temperature, in agreement with the author's observations. The dye then gradually continues to change until the reported activation temperature is reached (see the example given in Figure 2.1). The dyes from Matsui were observed by the author to change over a slightly longer temperature range compared to the other two suppliers. (LCR Hallcrest, n.d. and Matsui, n.d.)

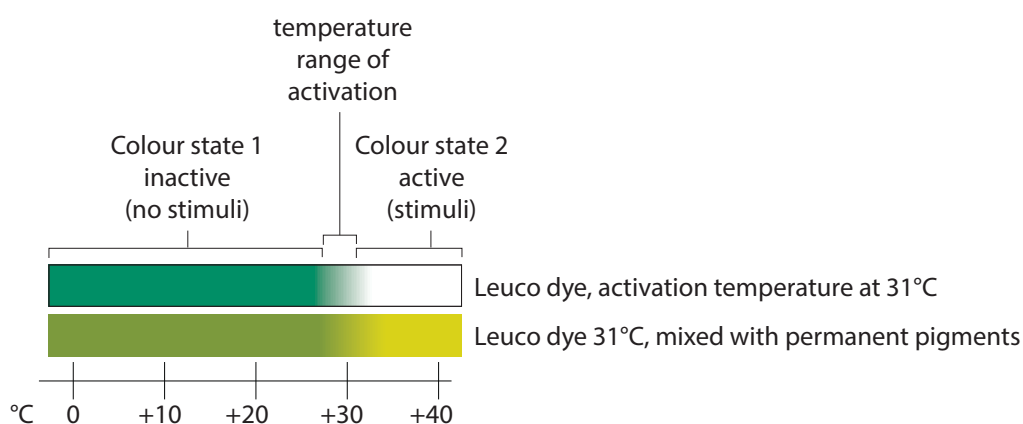


Figure 2.1 Graphic of the temperature range of activation using thermochromic leuco dyes.

Thermochromic liquid crystals demonstrate a colour change as the temperature is raised through a continuous colour spectrum of the rainbow. The liquid crystals should preferably be printed on a black background to provide more intense colour reactions. (LCR Hallcrest, n.d.) A structural feature of the liquid crystal, referred to as the pitch length, varies in relation to temperature, and causes the colour play to alter when the liquid crystals are heated. The relation between temperature and pitch length is non-linear, meaning that the time specific colours that are displayed differs as the liquid

crystals are heated steadily. The colour cycle starts with brown, red and then yellow, observed only fleetingly, and after that it proceeds through green and blue, which are visible for a progressively longer period of time. If the temperature increase is fast, the red and yellow colours become difficult to see. The cooling curve is normally flatter, and therefore all stages become easier to identify. Aspects of the colours can be enhanced by printing the liquid crystal onto a coloured rather than black background. For example, a red substrate intensifies the red colour and the green and blue colours become less bright. (Christie, Robertson and Taylor, 2007, pp.9-10; Robertson, 2011; Christie, 2013, pp.9-13)

The two types of thermochromic dyes can also be used together, as has been exemplified in Robertson's work (2011). A fabric that has been printed with a black (or dark) leuco dye has then been top coated with thermochromic liquid crystals. Both of the dye types demonstrated visible colour change when the liquid crystals had a lower activation temperature compared to the leuco dyes, providing colour play of the liquid crystals on the black leuco dye before it, in turn, becomes colourless. (Robertson, 2011, pp.116-117, 121-124, 130)

The leuco dyes are more UV-resistant compared to the liquid crystals. However, both dye types can degrade rapidly when exposed to UV-light. (Christie, Robertson and Taylor, 2007, p.7) The time over which the degradation occurs depends on the amount exposure to the UV-light. LCR Hallcrest states that their slurry based leuco dye will have an approximate lifespan of 600 hours in strong fluorescent light after which time the thermochromic effect might be damaged. (LCR Hallcrest, n.d.) XS-Lab found that thermochromic material they used had degraded over a period of months to the extent that it lost its ability to change colour (Berzowska and Bromley, 2007, p.4). However, there has been research carried out to improve the light stability of the dyes with laboratory results successfully reported demonstrating thermochromic solutions with enhanced light stability. (Christie, 2008, p.143) Ibrahim has found evidence that UV-absorber additives improve the light stability of slurry based leuco dyes. (Ibrahim, 2012, pp.130-144)

Another aspect to consider regarding the use of these dyes is exposure to certain chemicals or high temperatures. Although the dyes need to be heated to be activated, the molecules can, according to LCR Hallcrest, withstand temperatures of up to 200°C for shorter periods. The thermochromic dyes from Matsui are reported to withstand temperatures up to 130°C for short time periods. The material starts to degrade after 140°C. (LCR Hallcrest, n.d. and Matsui, n.d.)

Because thermochromic dyes are heat sensitive, the ambient temperature has an effect on the colour appearance. The warmer the ambient temperature, the less additional heat is needed to activate the dye. Thus, when working with thermochromic dyes, designers have to consider both ambient temperature and additional heating requirements throughout the application. (Ledendal, 2009, pp.17-18)

2.1.2 *Thermochromic dyes and environmental issues*

In terms of the environmental life span in relation to the ‘durability’ of a smart textile application using the two thermochromic dye types, in contrast with more traditional textile materials, leuco dyes are presently favoured over liquid crystals. The former is more UV-resistant compared to the latter and could thus be considered more sustainable in this respect. Arguably, the reversibility of thermochromic dyes could be perceived as negative in terms of the environment. The main issue is the fact that exposure to both UV-light and heat degrade the chemical substances of the material during activation. The lifespan of the material varies in relation to the conditions of illumination and how the material is handled, although there is promising research into extending their lifetime through the use of UV-absorbers, as discussed in section 2.1.1. (Christie, Robertson and Taylor, 2007, p.7; Christie, 2008, p.143; Fletcher, 2008, pp.164-166; Ibrahim, 2012, pp.130-144; LCR Hallcrest, n.d.) However, all textiles, in time, will degrade.

The fact that the thermochromic colour change within several current design applications is activated by electrical heat generation is another debatable environmental issue. (Seymour, 2008) If the change is being used only as an added effect, the energy has to be produced only for this purpose. In an interview on 15 October 2008, where Robertson discusses the energy usage, she argues that new knowledge of how thermochromic dyes function, by exploration of the use of electric current and research into conductive materials, might provide new circuitry solutions that can lead to more sustainable heating solutions. (Dr. S. Robertson 2008, pers.comm., 15 October) There is also on-going research into electrochromic materials, which change colour directly due to electric current flow. These materials only need power input, transported through the material, when one intends to initiate colour change. (Biever, 2006; Meunier, Cochrane and Koncar, 2011, pp.108-112) In contrast to electrically-heated thermochromic dyes, the current does not have to be applied continuously to provide continuous activity.

There are several questions raised in relation to the environmental issues of the chemicals in thermochromic dyes. The wall of the microcapsules in leuco dyes are made from formaldehyde as one ingredient. (Matsui, n.d.) The material is known to be carcinogenic and accumulates in living organisms as well as having an effect on human reproduction and development. There are scientific studies that provide conflicting opinions as to whether small amounts of formaldehyde cause this issue. (Formaldehyde Council, 2009) While free formaldehyde is not present in significant quantities in the product, research into new wall materials will be important for the future to minimise the consequences. When dyeing fabrics using thermochromic dyes, the fabric needs to be pre-treated with a bleaching process, such as hydrogen peroxide. (Shah, 2007, p.160; Matsui, n.d.) In the bleaching process stabilising additives are needed, some of them (such as sequestering agents) are highly polluting. However, hydrogen peroxide is one of the better alternatives from an environmental aspect in relation to bleaching a fabric or fibre. It is sometimes referred to as 'Green Bleach'. The dyeing process also needs a lot of energy and water. This is not an issue specifically with thermochromics but with all dyes. The environmental impact using the thermochromic dyes for printing varies depending on the printing technique used. An opinion has been expressed that digital inkjet printing is a more sustainable approach than screen-printing, a main reason being that less waste is produced. That makes the on-going research with inkjet printing of thermochromic dyes of great interest. (Christie, Shah and Wardman, 2009, p.5; Sharma, 2013)

To consider the situation as a whole regarding sustainability in relation to textiles, as with so many other products, is highly complex and difficult to reach definitive conclusions. Issues range from material production (for example pesticide use, water use, chemical additives, energy use, transportation, and packaging), issues regarding consumer use, to recycling the materials after the end of their life cycle. (Fletcher, 2008, pp.41-43; Chick and Micklethwaite, 2011, pp.106-107) It is difficult to differentiate smart from more traditional textile applications in this respect, due to the specifics of each individual textile application situation. An example of making an important improvement in the production chain of the textile might be by using more sustainable textile fibres and having the substrate fabric dyed with natural colours, although there are arguments that natural dyeing is not necessarily inherently sustainable. More sustainable fibres, compared to synthetic fibres based on fossil fuels or materials, such as cotton, that has a high use of fertilizers, pesticides and water are for example organic wool, hemp, wild silk, PLA,

lyocell, bamboo, soy, recycled fibres or organic as well as fair trade cotton that is produced with either less chemicals or a lower water use. (Bennett, 2012, pp.244-245, Sharma, 2013) Of course, moving towards a more eco-friendly textile fibre alone does not resolve the massive environmental problems of the textile. However, Fletcher highlights the importance of finding ‘small picture’ solutions (such as a better fibre) as well as to learn to deal with the ‘bigger picture’ in order to change the overall production chain towards a sustainable alternative. (Fletcher, 2008, pp.36-38) Another approach towards a more sustainable textile is to use locally produced materials, reducing transportation as well as assisting the local economy. Several textile products are shipped around the world more than once during their life cycle. Local production of the thermochromic materials might lead to difficulties because dyes are manufactured using specialist processes only in USA, UK and Japan. However, shipping only the thermochromic dyes and choosing low-impact transportation alternatives as well as using, as far as possible, local production might be a way to improve the environmental credentials of the end product. (Fletcher, 2008, pp.139-141; Shah, 2013, p.219; LCR Hallcrest, n.d. and Matsui, n.d.)

2.1.3 *Thermochromic dyes and textile construction techniques*

All suppliers of thermochromic leuco dyes have products that are suitable for screen-printing. Thermochromic dyes can be printed onto several different substrates. Robertson states in an interview on 15 October 2008 that she has not found any fibres that cannot be printed with the leuco dyes. Even wood and metal are appropriate, as long as the pigment is mixed with a binder that binds to the material substrate. (Dr. S. Robertson 2008, pers.comm., 15 October) To be able to create a visually clearer colour change, the dye needs a light substrate material. (Matsui, n.d.)

Printing with slurry based leuco dye is similar to printing with slurry based permanent pigments. Pigments are mixed with a binder to fix properly to a fibre. By mixing the pre-mixed slurry based leuco dye with a binder the printed surface is partly protected against cracking after curing. The binder also thickens the consistency of the paste, so it is easier to print through the mesh of the screen. As with traditional printing paste, the mix of the leuco dye and binder is smoothly applied with a squeegee. (Kinnersly-Taylor, 2011, pp.84-85; LCR Hallcrest, n.d. and Matsui, n.d) Ibrahim has investigated four different binders, Bricoprint Binder SF20E, BASF Perapret PU New, TMC Thermostar and Tego LA-B1096, in combination with slurry leuco dyes, to investigate whether properties such as colour strength, rubbing fastness, light fastness as

well as wash fastness can be improved. The tests were carried out at 2% dye strength with the magenta, orange, blue and green leuco dye slurries (supplied by LCR Hallcrest). Results showed that the TMC Thermostar binder provided the best performance. Ibrahim has investigated the relationship between colour strength and dye concentration for the leuco dye slurry and demonstrated an optimum at 30% concentration after which the colour strength started to decrease. (Ibrahim, 2012, pp.117-130)

The procedure of printing with powder based leuco dye is similar to that using traditional powder based printing dyes, i.e. the leuco powder also has to be dispersed in an additive and then mixed with a binder to provide a suitable consistency for printing. After printing, the material is dried and then cured with dry heat (normally for a 3-5 min at around 130°C). (LCR Hallcrest, n.d. and Matsui, n.d)

As well as screen-printing, thermochromic leuco dyes have been successfully (to some extent in a laboratory environment) applied to textiles using dyeing, inkjet printing and yarn extrusion. Matsui markets Chromicolor®, a water-based paste with clear dilutant and thinners, as used in the 'Aqualite Coloring System' pigment dyeing process for cotton fibres. The colour range is the same as that marketed for their dyes for screen-printing and can also be combined with permanent pigments. The dyeing process is customised for either the rotary or the smith drum-dyeing machines. Pre-treatment by bleaching of the fabric is often necessary for the colour-change to be more effective. (Matsui, n.d) Molnar and Tariverdian have carried out experimental investigations into dyeing skeins of yarns using slurry-based leuco dye and a vinegar-based dyeing recipe for protein-based fibres to fix the thermochromic dye. The experiments provided successful colour-change results after modifications in the original vinegar-based dye recipe, such as creating a leuco dye base that is more liquid compared with the slurry-based dye. (Johnson, 2009; Tariverdian, 2011) Niinimäki and Poula have experimented with weaving with yarns that they have dyed as well as painted with thermochromic leuco dyes. Their project 'Opodiphthera incognita' (2011) developed a dress that is intended to change in colour (due to the leuco dye) and shape (due to shape memory alloys) when the wearer is feeling threatened. (Niinimäki, 2011) Church has created another example of yarn that has been painted with thermochromic leuco dyes, which then has been woven into a fabric structure. The yarns are pastel multi coloured threads that becomes colourless when heated. (Codechromics, 2012) The leuco dyes were painted onto the yarns with a slightly diluted binder. (Dr. S. Robertson 2014, pers.comm., 18 February)

Recent research has shown that it is possible to screw extrude thermochromic yarns of ethylene vinyl acetate (EVA), polypropylene (PP) and linear low-density polyethylene (LLDP). The yarn was extruded with powder-based red and blue leuco dyes activated at 31°C (supplier LCR Hallcrest). At the current stage of development, the material is fragile, but the colour change is clear and the colour appears homogenous. However, the material has shown a decrease in colour strength after initial tests in drawing the yarn from room temperature up to 80°C. (Ibrahim, 2012, pp.144-179) The ability to produce thermochromic yarns by extrusion and dyeing creates exciting new design possibilities for the thermochromic material, when working with, for example, knitting or weaving, to create new colour-changing structures and patterns.

Christie, Shah and Wardman have successfully produced weak inkjet printed leuco dye prints onto cotton, by microfiltration of the dispersion before printing. Unfortunately, the microcapsule particles of the thermochromic material have shown tendencies to clog up the nozzles in the print heads. Tests have also indicated that it is feasible to inkjet print the three components of the leuco dye separately. (Prof. R. Christie 2008, pers.comm., 12 September; Christie, Shah and Wardman, 2009, p.5)

2.1.4 *Thermochromic dyes in design*

Over the last several years, there have been many design applications using thermochromic dyes. For example, they have been used to visualise communication, show the presence of humans and create dynamics in an expression or within a space and to invite play. As early as 1999, de Senneville created dresses that reacted to body temperature using thermochromic dyes, the first time such materials had been explored since Generra Sportswear's introduction of the Global Hypercolor T-shirts in 1991. (Lafee, 2001, Weinger, 2008) Within different applications in recent years, examples of designs may be found as an increasing number of researchers, artists and others have been experimenting with the dyes in new ways. In this section, a selection of the ideas is explained to outline the present status of the research within textile design involving the use of thermochromic dyes. Thermochromic materials can also be found applied to plastics, metals and other materials, but the applications presented focus on textiles, reflecting the research described within this thesis on thermochromics printed on textiles.

Textile interfaces are being used in different applications involving the communication of information as well as varying levels of metaphoric meaning. Colour-

changing chromic dyes are being used as a way to visualise this communication. Connecting the stimuli that activate the dyes to a computer-controlled system allows the colour change to be adapted to meet the needs of certain specific situations and applications. An example would be a move from a fast and obvious change to the effect becoming so discreet and the timeframe for the change so long that the user is not even aware that change is taking place. In 2003, Orth and the International Fashion Machines (IFM) constructed the wall-hanging ‘Dynamic Double Weave I’ (see Figures 2.2-2.3), one of the first documented examples of the use of thermochromic leuco dyes to create a textile display involving colour change based on the heat generated by electrically-conductive materials in a way that was computer-controlled. The system was created from a 64-pixel display, with individually controlled elements, which could create a rich variety of colour expressions. The colour change within the textile visualises the connection between a repeating textile pattern and a repeating software pattern. (Orth, 2004)

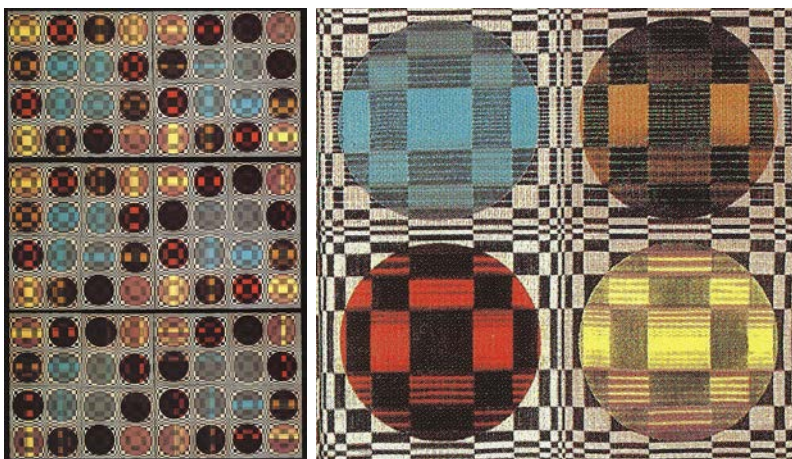


Figure 2.2 (left) ‘Dynamic Double Weave I’ by International Fashion Machines. Figure 2.3 Detail of textile (the original image is cropped), showing colour change in heated areas within the patterned circles (the darker hues have changed into more colourful hues, such as light blue, orange, red and yellow). (Braddock Clarke and O’Mahony, 2005, p.51)

The research group XS Labs, has used thermochromic dyes to visualise their work with electronic textiles and soft computation for new fashion solutions in garments that change colour. The dyes were chosen for their ability to create an interesting, but more subtle colour change in comparison to that produced by systems using emissive materials such as light-emitting diodes (LEDs), electroluminescence materials (ELs) or optical fibres. (Berzowska, 2005 p.3; Berzowska and Bromley, 2007, p.2) The ‘Animated Quilt’ (see Figures 2.4-2.5) was primarily recommended for interior and architectural applications, suited to the power requirements and heating issues involved. The

application created a black-grey-white colour change and, like ‘the Dynamic Double Weave I’, it has a pixel interface with individually controlled electronic elements providing multiple aesthetic expressions. (Berzowska and Bromley, 2007, p.11)

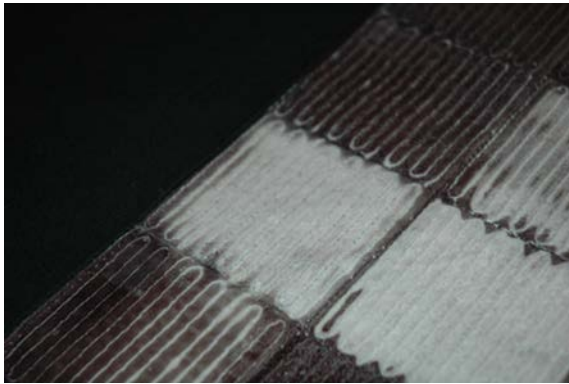


Figure 2.4 Close up of the ‘Animated Quilt’ by Berzowska and Bromley. The conductive threads have heated the black thermochromic dyed to change to colourless.



Figure 2.5 The textile is illustrated in two different activation scenarios (the original image is cropped). (Berzowska and Bromley, 2007, pp.2-3)

‘The Fabrication Bag’ (see Figures 2.6-2.7) is another project that visualises the communication between person and artefact (recipient and a mobile phone), and at the same time a communication between different individuals (caller and recipient). The visualisation in this example presents information in a more subdued way. The spotty pattern printed with thermochromic dyes changes colour (from dark grey to, for example, lighter green, red or blue) when a mobile phone connected inside the bag receives a call or a text, thus triggering a computer-controlled heating system. The bag provides a way of exploring how information affects the surroundings without being loud and noisy. The bag exemplifies Landin’s and Worbin’s discussion regarding the definition of ‘an interface’ and how aesthetics explore different ways in which

information may be displayed. The colour-changing material is used as a communicative bridge between the phone and the user. (Landin and Worbin, 2004)



Figure 2.6 (left) ‘the Fabrication bag’, 2005, by Landin and Worbin, Figure 2.7 (right) detail of pattern on bag, showing some thermochromic colour change in the spots. (Photography Worbin, L.; Worbin, 2010, p.117)

‘System 1’, by Berzina (see Figure 2.8), is a ‘tangible’ interface where colour change is visualized by electric stimuli causing a mimicking of the skin’s properties as it reacts to our nervous system. Through colour change, the surface becomes a communicative display, telling a story of how the system is functioning. Here again, the information level becomes dependent on the narrative symbolic meaning. (Seymour, 2008, p.183)



Figure 2.8 ‘System 1’ 2006, by Berzina. (Seymour, 2008, p.183)

A previous project of the author ‘Chromatic Chlorophyll’ also used colour change to provide an example of a more tangible interface. The users, patients in hospitals, rather than responding to information by hands-on feed-back methods (as using a computer, mobile phone or other device) respond on an emotional level (the colour change aims to trigger a feeling of being connected to one’s surroundings). The term

‘tangible’ in the context of this work relates to an interface in a general rather than specific sense. The leuco dye applications ‘rhythm of the house’ and ‘rhythm of the sun’ are aimed at interior walls and window hangings for hospital wards (see Figures 2.9-2.10). (Ledendal, 2009, pp.11-12)

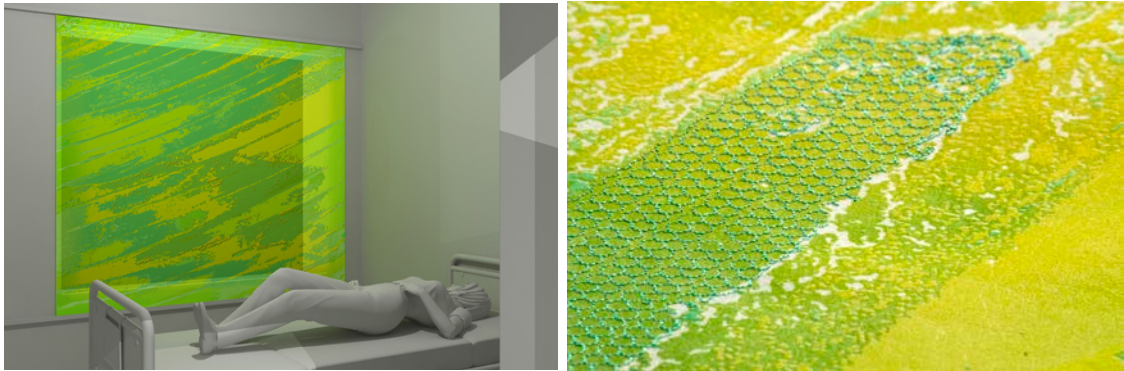


Figure 2.9 (left) Visualisation in a hospital ward of the conceptual idea of a window screen. Figure 2.10 (right) Textile demonstrating the colour change from green to yellow, 2009, by Ledendal. (Photography and 3D Imaginara)

When working with dynamic elements, the time of the change becomes of importance from both an aesthetic as well as a conceptual point of view. Ernevi et al., (2005a) discussed the concepts of ‘waiting’ and ‘slow communication’ through the project ‘Tic-Tac-Textiles’. The application is a playful scenario where leuco dyes create a communicative surface activated, either intentionally or by coincidence, from the heat of a coffee cup (see Figure 2.11). The project was constructed in two versions, consisting either of one or two module-based furniture. The one module based piece, Figure 2.11, is equipped with two sitting areas and one table surface. The two halves of the textile surfaces printed with thermochromic dyes are connected through a computer program, with sensors connected to each of the two halves of the textile table. This creates a mimic pattern on each half of the surface of the table, when one of halves is activated. The concept with two modules works in the same way, with the exception that the connected sensors are placed under each of the two textile surfaces of the two tables. This creates a mimic pattern on both tables when the surface on one of them is activated. The interaction only lasts as long as the cups are hot. The cooler the cups becomes the longer it takes to heat the surface to reach the temperature threshold to activate the sensor, which results in a slower information exchange. (Ernevi et al., 2005a)



Figure 2.11 One of the two tables in the interactive furniture 'Tic-Tac-Textile' by Ernevi et al. (Interactive Institute, n.d.a).

Several projects have investigated the communication between people in a cultural, social and emotional context, by exploring the colour change as a visualising tool. 'Spotty dresses', by Berzowska, involves prints with a camouflage-inspired pattern that is stated to encourage dancers in social situations to be freer and more animal-like in their behaviour (see Figure 2.12). The pattern disappears due to thermochromic change caused by the heat of human contact (either due to the wearers own body-heat or due to that transferred as other people touch the wearer) and in this way a story is conveyed about the interaction on the dance floor, for example. (XS-Labs, n.d.) Hodge has created several garments, such as the 'Touch me Luggage tag dress' (see Figure 2.13) and the 'Reveal and explore Micro-Organism dress', to investigate the social rules of touching. Hodge questions the narrative story by discussing whether the garment creates a bond between the individual touching and the wearer through touch memory, or rather creates a distance between the two. The thermochromic dyes are applied on areas of the garments, covering parts of the body, which might be considered more private to touch. Hodge states that the garments invite social and verbal interaction through body awareness and intimate touch. (Hodge, 2009)



Figure 2.12 (left) 'Spotty dresses' by Berzowska. (Berzowska, n.d.) Figure 2.13 (right) 'Touch me Luggage tag dress' by Hodge. (Hodge, 2009)

The project E-motion from the Institute of Fashion and Textile Design in Berlin, in 2009, investigated how fashion can create new cultural and emotional expression through new technology. Two of the garments produced as a result of the project included the use of thermochromic dyes. ‘The Shift’ (see Figures 2.16-2.17), by Dunkle, is a micro-controlled jacket that partly changes colour from black to blue when the wearer wants to communicate an emotional response. ‘Intimacy’ (see Figures 2.14-2.15), by Kempter, is another example of the project’s colour-changing garments. The dress creates a white pattern on the front through the heat generated by the integrated semi-conductive yarns, which is activated through touch sensors on the wearer’s back. The two garments both exemplify a connection between the wearer and other individuals, but from different perspectives; in the former, the wearer is in control of the colour change and in the latter he/she is not. (Schmidt-Thomsen et al., 2009, pp.9-10 and 13-16)



Figure 2.14-2.15 (top) The ‘Intimacy’ by Kempter. Figure 2.16-2.17 (below) The ‘the Shift’ by Dunkle. (Schmidt-Thomsen et al., 2009, pp.9-10 and 13-16)

An example that explores the relation between the space and people is the project ‘Costumes and Wall hanging’ from 2008 (see Figures 2.18-2.19). It is the person within the space that determines, not only the aesthetic outcome, but also the interaction between people. The performance piece by Bondesson, Persson and Worbin is an investigation into the interaction between the body and smart textiles where the leuco dye applied in the wall hanging is used to visualise the physical contact between the

dancers and their garment. The costumes contain sensors that can be activated either by the wearer or by one of the other two dancers. Depending on the combination of sensors being activated, different parts of the wall hanging change colour. (Swedish School of Textiles, 2009, pp.13-14)

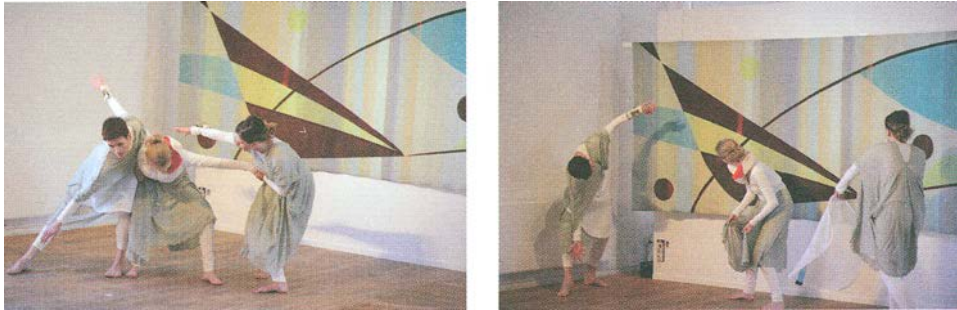


Figure 2.18-2.19 ‘Costumes and Wall hanging’ by Bondesson, Persson and Worbin, performance at Rydal Museum in Sweden, spring 2008. (Swedish School of Textiles, 2009, p.13)

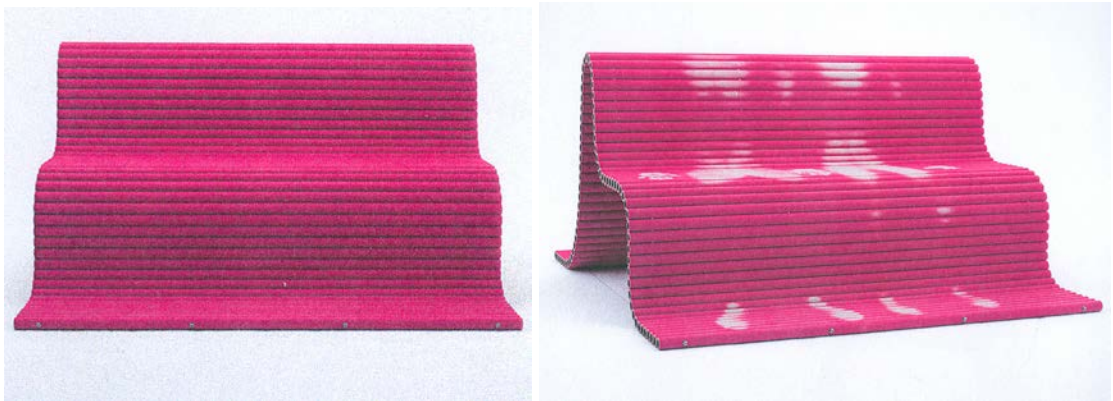


Figure 2.20-2.21 ‘Temperature-Sensitive Furniture’ by Shigeru BAN. The sofa is cold and all pink (left). White shapes (right), from the warmth from an individual’s body heat, appear on the surface when someone has been sitting in it. (Tokyo Fibre, 2007, pp.131-132)

Thermochromic dyes have been used to visualise a previous presence within a space or place by way of a mark left behind within that space. The touch memory system of the thermochromic dyes, which is due to the fact that the dye does not immediately change back to its inactive colour state after the thermal activator has been removed, has been used in such applications. The piece ‘Temperature-Sensitive Furniture’ (see Figure 2.20-2.21) by Shigeru Ban illustrates this effect through the white marks in shapes due to human contact that are left on the coated pink sofa after use. (Tokyo Fibre, 2007, pp.126-133) Other examples of furniture printed with thermochromic dyes are the pink ‘Warm-Up Table’ (2002), by the architect firm J.

Mayer. H. and the black, 'Linger A Little Longer' (2011) by Jay Watson. (Mayer, 2002 and Watson, 2011)

Other sources of information to create visualisations concerning the environment through the use of thermochromic materials, have been displayed using appropriate material resources and digital data, in order to generate awareness and action aiming to create a better climate. Van der Maas et al., have investigated the potential for thermochromic printed surfaces to communicate the indoor climate in architectural applications. This team has explored the possibility of constructing a large-scale prototype using printed circuits boards and a modular based system. The thermochromic materials were chosen because of their more subtle expression and non-emissive properties. (Van der Maas et al., n.d., pp.1-2) In contrast to 'the Fabrication bag', which displays direct communication between people and the bag, 'Inside/Outside' by Moriwaki involves a bag, which visualises environmental information. The application uses an air quality sensor and an audio microphone connected to a microcontroller and conductive yarns within the bag. The heating effects caused by reaction to the sensors causes colour changes on parts of the patterned thermochromic surface, which in turn creates connections between the wearer and the urban space as well as other individuals. By registering the ambient air quality and the noise levels, the bag becomes a movable display in the city, while constantly updating local environmental information. (Celatti, 2008)

'Disappearing-Pattern Tiles' by the Interactive Institute in Sweden discusses the overuse of water and energy by causing the ceramic tiles in a bathroom to lose their pattern when the room gets too hot due to overuse. (Interactive Institute, n.d.b) Several examples of lampshades have been designed based on the idea of the use of dynamic thermochromic properties to communicate visually to the user that it is time to turn off the light or to use an energy-saving bulb. These lamps, for example 'Poster lamp' by Hevicon, generally provide a change in colour or a disappearance of patterns. (Hevicon, 2008) American Apparel has used the colour change of thermochromic dyes to visualise how the area of the Polar Ice Cap diminished from 1989 to 2009. The T-shirt contains an image, which on heating due to the wearer or a high ambient temperature reveals the 2009 scenario. The dyes thus become the tool to create the platform for the two realities with the human body as the display. (Webelowwear, 2009) Earl and Newman have created a conceptual textile membrane for Abu Dhabi Airport in a design submission for the 2010 'Land Art Generator Initiative Design

Competition', where the thermochromic dye coated sculpture is designed to act as an indicator of the amount of solar activity that has been harvested by photovoltaics, as well as a visual thermometer to display ambient temperature. (Earl and Newman, 2010) This conceptual idea was the only example that the author could find that combines photovoltaics and thermochromic dyes within one and the same object. However, the author can only speculate on the connection between the two parts, due to the limited information reported. For example, there is no information indicating that the energy harvested by the photovoltaics is used to activate the thermochromic dyes, as carried out through the work described within this thesis. The information about the textile membrane for Abu Dhabi Airport only states that the dye is believed to be used as an 'indicator of solar activity'.

There has also been research into and experimentation carried out using thermochromic materials with a focus on how the dyes and the colour change that they provide affect the surface and the heart of the artefacts. Berzina's 'Skin Stories' investigated the use of the textile surface as a second and a third skin, integrating smart materials with membrane-like qualities of the human skin. The material's reaction activated by stimuli creates interactive surfaces related to the body and its functions. The work 'Skin Stories' is stated to have a focus on the aesthetics of the textile and their relation between the science and the dynamics of the materials. (Berzina, 2004, pp.281-282) The aesthetics of the textiles were partly determined by way of the materials that were chosen according to the aim of mimicking the properties of the human skin. (Berzina, 2004, p.225) In 'Sensory Screens' (see Figure 2.22) the thermochromic leuco dye becomes the pulse of the 'living skin', through heat stimuli provided by conductive threads and dyes incorporated in the textile. (Berzina, 2004, p.220) In 'Touch-Me Wallpaper' (see Figures 2.23-2.24) the leuco dye brings an interactive playful element into the concept, whereby people in the room become part of the change within the design. Until they have reversed back to their original state, dynamic patterns appear as recordings of the interaction between viewer and wall. (Berzina, 2004, pp.245-249) In 'Sense Wallpaper', Berzina exemplifies the skin's sensory activity with the colour change of the liquid crystal, where the conductive impulse in the fabric becomes a metaphor for psychological and physical stimuli. (Berzina, 2004, pp.253-258)

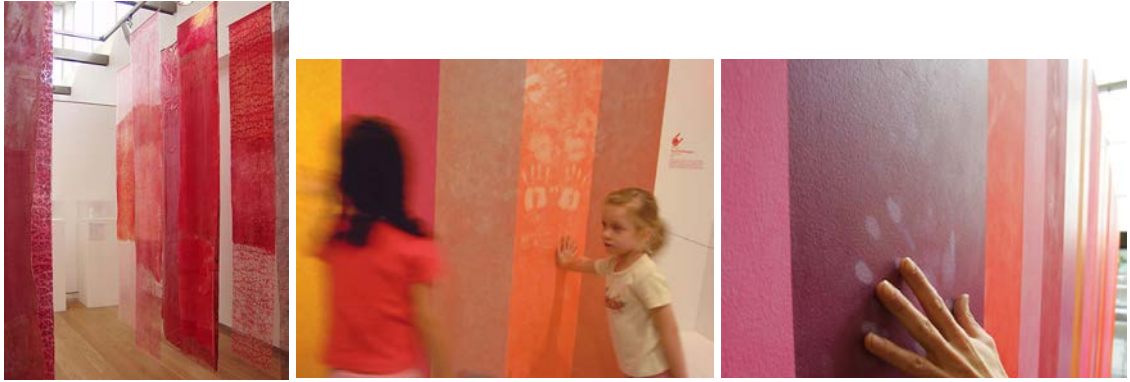


Figure 2.22 (left) ‘Sensory Screens’, 2004 and Figures 2.23-2.24 (centre and right) ‘Touch Me Wallpaper’, by Berzina. (Berzina n.d.)

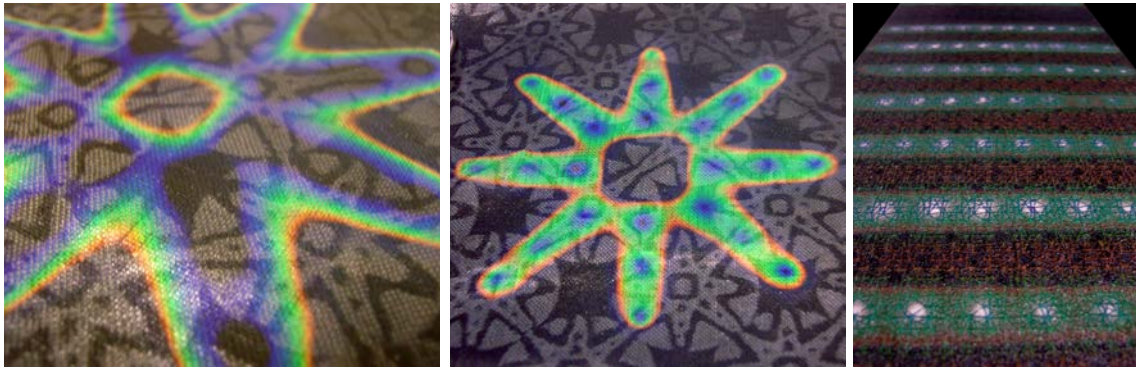
Another, more recent, project with thermochromic leuco dyes that explores the potential of the aesthetic qualities of colour changing textile surfaces is ‘Smart Costumes’ by Aylett, Calder, Louchart and Robertson (see Figures 2.25-2.26). The project explores the potential of the dye in the context of performance costumes, where activation and inactivation is explored thorough a software system controlled by a Kinect sensor (colour sensitive sensor). The project also explores the potential to create a programmable textile surface through 3D printed polymers. (Calder et al., 2013a and 2013b)



Figure 2.25 (left) inactivated and Figure 2.26 (right) activated tutu in ‘Smart Costumes’ by Aylett et al. (Photographer Calder, L.)

Most research in design conducted with thermochromic dyes has focused on applications with the leuco dye type. However, Robertson has performed in-depth investigations of the possibilities and colour play with the liquid crystal type. The aim in this case was to explore the potential of surface structures with the thermochromic liquid crystal material in combination with electronically-controllable heating systems. Robertson created subtle colour changes by experimenting with laser etching

technology as well as creating rich colour applications through novel surface treatments applied to textiles printed with the thermochromic liquid crystals, some in combination with thermochromic leuco dyes (see Figures 2.27-2.29). (Robertson, 2011)



Figures 2.27-2.29 Textiles printed with liquid crystal by Robertson (Photographer Roberson, S.)

Different artists and designers have investigated the possibility to use chromic dyes to enhance niche market applications. Ding's 'Aqua Chameleon Collection' explores the aesthetics of thermochromic dyes, in combination with photochromic and water-reactive dyes, for future possibilities in swimsuits. (Collet, 2007, p.17) The aesthetic dynamic effects have been used in ready-to-wear fashion applications as well as for interiors. In 2007, Chang presented a velveteen coatdress printed with a thermochromic camouflage pattern (see Figure 2.31). In a 2008 collection, Chang designed a top that shows a print of a red map when the dye was activated by the body heat (see Figure 2.30). (Seymour, 2008, pp.35-37)



Figure 2.30-2.31: Garments from 2007 and 2008's collection by Chang with applications of the thermochromic dyes. (Seymour, 2008, p.36)

Kooroshnia has explored whether objects might be personalised and made interactive by way of variations in seasonal and indoor and/or outdoor temperatures.

Kooroshnia has produced, as an example, the facial mask shown in Figures 2.32-2.33, a type of garment, which is becoming more popular to minimise harm from pollutants and threats of health epidemics. (Kooroshnia, 2009, p.13)



Figure 2.32 (left) The inactive pattern element (subdued colours) and Figure 2.33 (right) the active pattern element (brighter colours) demonstrates an example of the colour-changing effects in Kooroshnia's Mask. (Kooroshnia, 2011)

2.1.5 *Heat sources to activate thermochromic dyes*

The heat sources that have previously been used to activate the colour change of thermochromic dyes within design research for applications with thermochromic dyes and the design examples discussed in section 2.1.4 are mostly electrical heating, warm air or warm liquids, body warmth and a high enough ambient temperature.



Figure 2.34 (left) 'Graffiti Cloth', by Persson and Worbin (the original image is cropped). (Worbin, 2010, p.191) Figure 2.35 (right) detail of the textile 'Graffiti Cloth', heated with a fan. (Worbin, 2010, p.184)

The use of warm air, for example fans in the project 'Graffiti Cloth', Figures 2.34-2.35, or the warmth of the human breath in 'Mask', Figures 2.32-2.33, creates colour

changed imageries depending on the angle of the hot/warm air source as well as the distance between the textile surface and the source. (Kooroshnia, 2009, p.13; Worbin, 2010, pp.170-193)



Figure 2.36 (left) Mug with hot water on a tablecloth printed with pink thermochromic dye, from 'Textile Disobedience', by Worbin. Figure 2.37 (right) The hot water that is poured out has changed the colour of the textile. (Worbin, 2019, p.67)

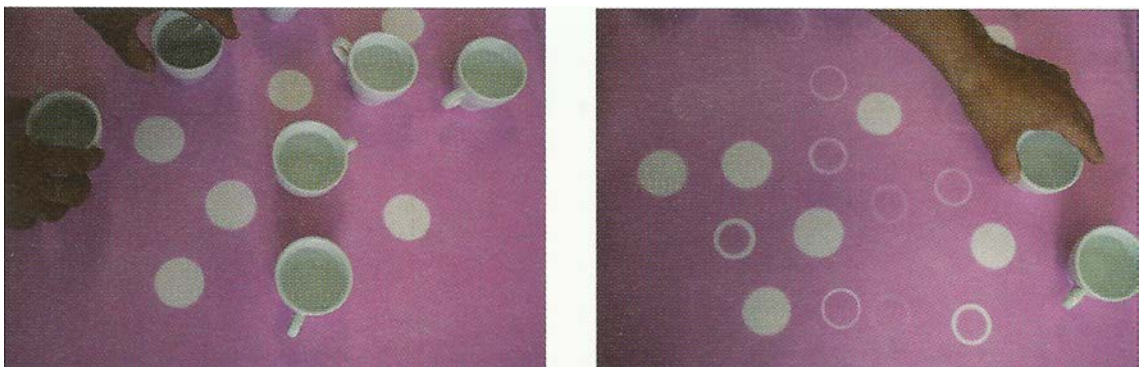


Figure 2.38-2.39 'Do the Pattern Yourself', mug with hot water on a tablecloth printed with pink thermochromic dye, from 'Textile Disobedience', by Worbin. (Worbin, 2019, p.59)

Whereas hot liquids create direct surface changes of the imagery similar to either the shape of the hot water poured on the textile, see Figures 2.36-2.37, or to the shape of the surface of the container that stores the hot liquid in contact with the textile, such as the bottom of the cups with hot water in the project 'Do the Pattern Yourself', see Figures 2.38-2.39. (Worbin, 2010, pp.58-67) This is quite similar in terms of shape to the colour changed imagery that is created through body heat. The colour-changed imagery that is created on the textile printed with thermochromic dyes is closely connected to the shape of the part of the touching body, such as the body prints on the 'Temperature-Sensitive Furniture' or the hand prints on 'Touch Me Wallpaper', see Figures 2.21 and 2.23-2.24. (Berzina, 2004, pp.243-258; Tokyo Fibre, 2007, pp.126-133) The thermal energy created by body heat demands a touch sensitive

thermochromic dye, with an activation temperature around 30°C. (LCR Hallcrest, n.d.) The rate of the colour change appears to be affected to some extent by the thickness of the textile material, when it is worn as a garment. (Worbin, 2010, p.149)

Electrical heating solutions, for example using heating elements, are controlled and powered by electrical current. An electrically-conductive material that is effective for activating colour change in a thermochromic dye is required to be ‘an inefficient conductor’, since such a material provides a higher level of thermal energy than an efficient conductor. (Berzowska and Bromley, 2007, p.4-5) A material with high resistance (meaning low conductivity) is capable of producing a high level of thermal energy. The resistance of a material is measured in ohms (Ω). A resistor may be used to control the flow of electricity within a circuit, analogous to the way that the size of a water pipe regulates the rate of the flow of the water. (Harrop, 2009a, p.5)

There are different versions of surface-mounted resistor technologies that might be used to heat and control the activation of a textile treated with thermochromic dyes. Heating elements can, for example, be custom-printed circuit boards mapping the design that is intended to change colour. These are, however, currently very expensive to produce, especially for a small number of samples. (Ledendal, 2009, p.19; Worbin, 2010, pp.82-83) Printed circuit boards may be constructed in several thicknesses (providing different flexibility and stiffness properties) and can be integrated with microcontrollers to control the heating elements of the board. (Van der Maas et al., n.d., pp.8-9)

Other conductive materials tested for electrical heating solutions include metals, conductive yarns and printable conductive inks. (Berzina, 2004, p.153) Examples of conductive yarns on the market today are stainless steel, carbon, copper, silver threads and mixed yarns such as Bekaert’s VN12 and VN14 thread or Karl Grimm’s Hight Flex 3981 bare copper or thinned copper. A conductive thread is normally prepared by spinning or twisting a traditional textile with a conductive material, such as a silver or stainless steel. (Berzowska and Bromley, 2007, pp.5-6) The carbon yarn is an example of a material with a very high temperature resistance. (Braddock Clarke and O’Mahony, 2005, pp.62-63) The conductive threads can be integrated, creating a heating circuit or element, within the textile through weaving, knitting, stitching or embroidery. The conductive material behaves differently according to how the thread is angled, the closeness of the conductive threads, and levels of voltage and current (ampere). These parameters, additionally, have a strong influence on the aesthetic

outcome. The aesthetic outcome of the colour-change imagery, due to the influence of these parameters, is to some extent also governed by chance. Even if the designer can control the different design parameters, it can still be difficult to predefine an exact end result, due to the sensitivity of the influence of current flow on the amount of thermal energy produced in particular circuit situations. This 'randomness' might, however, be perceived as an interesting added design variable. (Ledendal, 2009, pp.18-19)

An example of conductive ink is carbon 7102 Conductor Paste, a high resistance yarn that is supplied by DuPont. (Berzina, 2004, p.153) In 2009, 'Bare', a water-based conductive ink, was presented. The conductive ink, by directly painting on the human skin, is considered to provide a seamless bridge between human and technology, creating an innovative interface. (Johnson et al., 2009) 'Bare' has, however, so far not been used in applications with thermochromic dyes.

Different conductive materials can be used to transport electricity with different resistances for different functions, depending on the detail of the circuit design. A yarn with low conductivity (high resistance) might, for example, be used to create heat to activate a thermochromic material, whereas a highly conductive yarn might, for example, be used to transport information between a textile and a computer program or sensor. (Orth, 2003) In the project 'Animated Quilt', XS-Lab used a metallic silver organza (a silk warp and a silver wrapped weft) to create low-resistance connections. (Berzowska and Bromley, 2007, p.7)

Robertson (2011) has, on the basis of experimental design-led research, established relationships between the heating time, as heat is generated, and the voltage that is needed to control a pattern with different temperature sensitive thermochromic dyes (both liquid crystal as well as leuco dye). Robertson created a design system using circuits containing 150 Ω copper resistors with a dimension of 10mm x 5mm and with a 1mm distance between each copper resistor. A non-patterned fabric formed, in time, a linear design on the printed surface that covered the connected resistors on the circuit board, via a pattern of individual rectangular shapes that was initially formed on the fabric on top of each resistor. A leuco dye, with an activation temperature of 47°C, printed onto cotton, for example, needed the application of 7V over 5 minutes to create the final design. A colour change in the area on the fabric above the resistors became visible after 1 minute and after 3 minutes a central heat-spot was created, with the colour change starting to spread further on top of the area of the copper surface. This pattern required a cooling down

time of 3 minutes to revert to its initial state. A voltage of 5V was needed to create the same final design when a leuco dye with an activation temperature of 31°C was used. Robertson could not find any notable difference in the heating times, as long as the weight of the fabric was similar to the cotton originally used. A 36°C colour start liquid crystal moved through its complete colour spectrum using a voltage of 4.25V and had achieved its isotropic state after 10 minutes. The sample required a cooling down time of 8 minutes to show the reverse colour change. A 36/37°C liquid crystal provided the same effect after 5 minutes with a voltage of 4.75V and required a cooling down time of 5 minutes. Robertson established a relationship between the heating and the cooling times for several of the tested fibre substrates printed with liquid crystals using a voltage of 7V. The cooling time generally proved to be roughly half the heating time. Plastic films, however, demonstrated a 1:1 ratio in this respect. (Robertson, 2011)

There is, as demonstrated through section 2.1.4, essentially no prior reports of research into the use of sunlight as an activator of thermochromic dyes. However, the sun as an activator has been explored in research and design applications using photochromic dyes, which initiate colour formation through UV-sensitivity. (Zane, 2004; Seymour, 2008, p.37; Hodge, 2009; Schmidt-Thomsen et al., 2009; Christie, 2013, p.16) The author considered using the thermal energy from sunlight to activate thermochromic dyes, in previous conceptual work. One initial indoor experiment with a nonwoven textile printed using a thermochromic leuco dye with an activation temperature at 27°C was carried out, to establish whether the concept had validity. In this experiment, the sunlight showed potential for use as an activator of colour change, but practical work was at that point not taken any further due to time limitations. (Ledendal, 2009)

2.2 Design methodology

When conducting research towards a designed textile artefact, there are many research approaches that can be taken, reflecting the diverse nature of the discipline. Research is a systematic process of enquiry and as such, requires a methodological model appropriate to the interdisciplinary nature of the research.

‘Design methodology’ as a concept worthy of exploration and evaluation, was established in the mid 1960s, initiated in the 1962 ‘Conference on Design Methods’ in London. Previously unexplored aspects of the designer’s practice were investigated in measurable terms and set out as design research ‘methods’, such as emphasis on the

user, use of basic research methods to validate views with fact, use of ‘brain-storming’ and ‘disruptive’ thinking and an increase in examining the collaborative nature of design with other disciplines. The field struggled with its legitimacy during the 1970s, but experienced an upswing through research publications, conferences and establishment of academic journals during the 1980s and 1990s. (Cross, 1993, pp.15-23) Furthermore, the 1990s saw the start of the field of ‘practice based research’ within the Art and Design discipline, involving new knowledge provided as the outcome of practical, original investigations. (Grey and Malins, p.3) Design methodology has developed dramatically since the 1990s and there are currently many researchers working with different aspects of the approaches that it adopts. The number of conferences and workshops within the area has increased over this period and there is now an established research community who research methodology as a research outcome in itself. (Birkhofer, 2011, p.1) Kroes (2002) states that methodologies involved in design are more process oriented, and that scientific method, on the other hand, is more a product oriented, descriptive practice. (Kroes, 2002, pp.282-288)

From this viewpoint, it can be demonstrated that the methodology for the research within this thesis, involving design motivations, aesthetic outcomes and innovative, technologically led practices, cannot be prescribed or easily defined using established terminologies. Traditionally, for a textile designer, the aim of the design process applied to textiles can be defined as the outcome of a number of applied consecutive design methods. This process creates and produces a textile product, normally within a set time frame. (Wilson, 2001, p.10) The design process often includes the initial ‘design brief’, which provides a framework for the end product(s). The final results are generally reached by the textile designer through the experimentation and use of a series of ‘design variables’, such as colour, shape, imagery, material and construction techniques, in relation to the ‘basic textile principles’ of scale, texture, colour/colourways, imagery, repeat, placement and weight. (Udale, 2008, pp.24-31; Russell, 2011, pp.46-49) However, this ‘traditional’ approach, both in relation to the end product and the design process is not always applicable when working with smart textile applications or materials. Although one or more of the ‘general’ textile design methods are still applicable when working with Smart Textiles, a complementary set of design methods is sometimes needed. (Worbin, 2010, pp.20-24)

2.2.1 *Design methods relevant to the use of thermochromic dyes and ‘reversible dynamic patterns’*

This section discusses the design methods relevant when using thermochromic dyes and the broader aspects of ‘reversible dynamic patterns’ within textile design applications.

Over the past decade, a number of designers, as described and examined in section 2.1.4, have experimented with and explored the possibilities of designing with dynamic surfaces incorporating thermochromic dyes, through such projects as ‘Dynamic Double Weave I’ and ‘Animated Quilt’. (Orth, 2003; Berzowska, 2004; Berzowska and Bromley, 2007) However, there remain a limited number of publications on design methods in relation to reversible dynamic imageries in general, as well as in the use of thermochromic dyes specifically.

Linda Worbin is one of the most prominent researchers within the field of design methods for reversible dynamic imageries based on surface changing materials, such as those provided by the use of thermochromic leuco dyes. Worbin (2010), defines a ‘reversible dynamic pattern’ by the description (*A B A*), which indicates that the design changes from one static imagery (*A*) to another static imagery (*B*) and then back to (*A*) again. Worbin argues that the dynamic process has the potential to change into one or more possible expressions. (Worbin, 2010, p.49) Worbin has presented a set of ‘dynamic design variables’ for designers to relate to when working with surface changing materials; ‘material and techniques’, ‘time’, ‘interaction’, ‘surroundings/ambience’ as well as ‘dynamic form expression’. These design variables were developed based on empirical work carried out using eight design examples. Worbin argues that the differences between ‘conventional’ expressions (form, line, space and colour) and ‘dynamic’ expressions are associated with the former having a static structure while the latter can change over time, between different conventional expressions via transformative stages. Worbin, demonstrates in a number of the design examples, how incorporating digital information, either randomly or by programming, can control the aesthetic outcome of dynamic imageries. In addition, Worbin provides a number of ‘basic design principles’ that the designer may consider when working with dynamic imageries for textiles. She suggests that the designer needs to let go of conventional thinking related to the design of textile imageries and that they need to be aware of the object/material, which will initiate the change. Furthermore, the designer needs to consider whether the activator of the dynamic

material involves an external source or is integrated within the material, and whether the response is immediate or there is a delay. (Worbin, 2010, pp.261-270)

An amendment to Worbin's ($A \ B \ A$) definition was proposed by Nilsson et al. (2011), there among Worbin herself, to include the transition between the two stages A and B . The amendment included two identical arrows as ($A \rightarrow B \rightarrow A$). In this case, the colours that the thermochromic dyes exhibit during their transition are defined as a 'colour scale of nuances' created from the inactive colour through to complete activation of the dye. Nilsson et al. state that these nuances can be partly adjusted by mixing thermochromic leuco dyes with different activation temperatures creating the possibility for alternative visible hues as a result of the phased transitions. (Nilsson et al., 2011)

Berzina (2004) has formulated the 'Versicolour System' as a method to explain the principle of colour change of textiles printed with either thermochromic leuco dyes or thermochromic liquid crystals, for interactive textile applications. The Versicolour System is used to explain colour changes when moving from coloured to colourless or from one colour to another colour using the leuco dye type (the latter alternative involves a mixture with permanent pigments). This feature is explained in section 2.1.1 and illustrated in Figure 2.1 in this thesis. The Versicolour System may also be used to explain the colour play over a selected temperature range given by the liquid crystal type, as explained in section 2.1.1. The system can be designed either to allow creation from a uniform colour change (given a uniform temperature rise over the entire surface) or from a colour change within imageries consisting of lines, blocks or freer forms for example. (Berzina, 2004, pp.175-176)

Kooroshnia (2013a) has presented an approach to convey the principles involved in mixing thermochromic leuco dyes, for use in fashion and textile design education. The method is practice based and uses hands-on teaching methods and laboratory exercises. The method is based on swatches printed with thermochromic dyes, some mixed with permanent pigments, which were chosen systematically to provide a fundamental explanation of the principles. (Kooroshnia, 2013b) The exercises are conducted to provide an understanding of the behaviour of the thermochromic dyes at above or below ambient temperature, in relation to the chosen activation temperatures. Additionally, the exercises provide an understanding of the effects on the aesthetic outcome of the design, in relation to the visual outcome from the activation of the dyes. (Kooroshnia, 2013a)

In addition, Berzina (2004) has formulated the ‘Multicolour Chromic Design System’ as a method to explain the complexity of the principles involved when building up surface imagery for applications using interactive textiles that incorporate thermochromic leuco dyes with different activation temperatures. The system recognises that the coloured layers closest to the fabric are required to be the ‘lightest’ and the top layer the ‘darkest’ colour. (Berzina, 2004, pp.183-184)

Robertson et al. (2011) have created a method to visualise the colours in conceptual designs that use thermochromic liquid crystals. The method involved the investigation of the colour play of textiles that are printed with two layers of liquid crystals. This is based on a variable-temperature colour measurement analysis methodology using a programmable Linkam TH600 hot-stage with a PR600 temperature controller, held tight against an aperture of Datacolor Spectraflash SF600 reflectance spectrometer. The data obtained from the liquid crystals are imported into Adobe Photoshop and visualised through a custom-devised colour indexation process. (Robertson et al., 2011, pp.113-119) The method was based on the discovery that additional colours, such as turquoise, lilac and purple, were created when the two layers of liquid crystals with different temperature thresholds were printed. These additional colours appeared to be created through the principle of additive colour mixing rather than of subtractive colour mixing, as might have been expected. (Robertson, 2011, pp.111-123)

2.3 An introduction to sun-screening: Sunlight as a renewable energy source and the use of photovoltaic solar cells

This section introduces applications that involve both sunlight and textiles: sun-screening textiles and electronic textiles that are powered by photovoltaic solar cells. The section also includes general information regarding solar energy, and the development of photovoltaics and the photovoltaic market.

The fact that sunlight has several positive effects on the human body, such as stimulating production of vitamin D as well as regulating the biological rhythm, was recognised in the 1970s. (Wurtman, 1972) However, sunlight can also have more bothersome and negative effects on humans due to over-exposure, such as dehydration and sunburn. In certain situations, these side effects can be overcome or reduced by the use of sun-screening textiles. Outdoor shaded areas can provide a feeling of coolness, due to reduced evaporation of water from the body, as well as directly lowering the amount of radiation from the sun that impacts on the skin. Shading can also be used to

lower indoor temperatures in situations where they would otherwise be too high due to strong sunlight. (Schattenzelte, 1984; Kronenburg, 1995; Dubois, 2001; Bellia, Falco and Minichello, 2013)

Due to the fragility of textile materials, it has proved difficult to find ancient textile artefacts that provide direct evidence for when humans started to use sun-screening textiles for such indoor and outdoor purposes. However, researchers have found illustrations as well as artefacts from graves that point to them being used in the very first buildings. (Krüger, 2009, p.26) Krüger states, using a number of examples, that historical findings demonstrate that the ancient civilisations would have used textiles both as decoration and as shelter from sun, weather and to obscure the view. The Romans, for example, converted fabric into sun-protecting extensions above the porch. (Krüger, 2009, p.91) Other uses of such textiles in public buildings by ancient cultures have been established. For example, amphitheatres were covered with large, sun protecting, retractable roofs (vela roofs). (Kronenburg, 1995, pp.27-37) Smaller, portable versions of sun sails, parasols, were used both in ancient Egypt and the ancient Orient. These parasols were originally aimed at providing protection from sunlight rather than rain. (Krüger, 2009, pp.93-94) Rectangular sun shading textiles (toldos¹) were, in past times, strapped between houses in streets in public areas within cities. They are still used in cities in several south European countries, such as Seville in Spain as well as in cities in South America and Japan, for example. (Schattenzelte, 1984)

The use of outdoor textile roofs within modern urban spaces has developed over the past century. Frei Otto, a German architect and structural engineer, is one of the main contemporary pioneers. He started to develop lightweight, membrane constructions after the Second World War. One of the first retractable, membrane constructions was built in the mid 1960s over the ruins of an abbey in Bad Hersfeld in Germany. (Kobayashi and Sharp, 2002, p.9) The concept was developed further so that such textiles are frequently used today in sports arenas, airports and railway stations, to name but a few, often providing an organic expression (see Figure 2.40). (Krüger, 2009, p.92)

¹ Toldos (Spanish), meaning awnings in English, are to with commonly referred its being Spanish word also in English texts. (Schattenzelte, 1984; Krüger, 2009)



Figure 2.40 The Tubaloon, Kongsberg Jazz Festival, by Snøhetta, Norway, 2006, an example of a textile membrane for urban outdoor applications. (Krüger, 2009, p.134)



Figure 2.41 (left) The Arium at the ISCID conference, 2003, by J. Mayer H. Architects. Figure 2.42 (right) The Swiss Pavilion for Arco, 2003, by 2B Architects. (Krüger, 2009, pp.126 and 133)



Figures 2.43-2.44 Examples by Renate Buser, the Littmann Kulturprojekte, 2008. (Krüger, 2009, p.131)

In the 1970s, Otto conducted the project ‘Shadow in the Desert’, successfully demonstrating the efficiency of the screening effect from sunlight using horizontally

placed textiles. The system was constructed with horizontally stretched nets, which proved successful in increasing water conservation by the reduction of water evaporation within the desert. (Bubner and Otto, 1972) A variety of innovative designs with a range of ideas regarding pattern and motifs on sun-screening textiles have been exhibited by a number of different designers over the last decades. Some examples are: imagery cut sun sails for the venue for the International Society for Complexity, Information, and Design conference (ISCID), 2003, vinyl printed canvas in Basel, 2008 or the Swiss flag-shaped light and shadow installation at the Swiss Pavilion, Madrid, 2003 (see Figures 2.41-2.44). (2B Achitectes, 2003; Mayer, 2003; Littmann, 2008)

Over recent decades, there has been an expansion in the number of office buildings with constructions containing large windows, and this can result in high indoor temperatures and problems with the visual environment. The elevated indoor temperatures require increased use of cooling systems, which in turn increase both energy use and costs. (Dubois, 2001, p.13) The increased incidence of sunlight in office areas additionally resulted in complaints from workers due to problems with glare and other visual disturbances. (Christoffersen et al., 1999, pp.7-8) Today's extensive use of computers within office environments has added to these problems because windows often are directly or indirectly (through reflections in the computer screen) in the workers' field of view. Using sunscreens on or in front of the windows in these buildings has proved to lower the ambient temperature in the facility via a decrease in thermal transmission through the windowpanes. (Bellia, Falco and Minichello, 2013, pp.190-201) Sun-screening solutions have also proved helpful in solving problems concerning glare. Additionally, shading devices can result in better light distribution within the room, depending on their construction, as well as reducing heat loss through the windowpane during the night. (Dubois, 2001, p.14)

In the past, the horizontal textile was used as a status symbol, in addition to providing shade. For example, in ancient Egypt, royals and nobles travelled under baldachins (canopies) and umbrellas. Ceremonial baldachins were still in use in Europe until the late nineteenth-century. To this day, such textile canopies are still being using in some religious rituals. (Krüger, 2009, pp.90-94)

2.3.1

The sun as a renewable energy source

Renewable energy sources are an essential part of a more sustainable lifestyle. Examples of renewable sources of energy are sunlight, wind, rain, tides and geothermal heat. Solar energy is ‘an intermittent energy source’, which means that it is not always available at any one specific place on earth, due to factors outside our control. This means that there will be the need to complement this alternative energy source when used to power systems. However, since the sun is not going to burn out for a very long time, there is immense potential for its use as a renewable energy source. It is estimated that the amount of energy that the sun produces measures roughly five times the total energy consumption of our entire planet. (Smith, 2001, p.37) However, in 2012 solar energy only accounted for 0.5% of the global electricity supply. This is miniscule compared to the global use of traditional energy sources such as coal (42%), natural gas (21%), hydro (15%) and nuclear (12%) for the same year. (Wilson, 2013) However, the future of photovoltaic cells to harvest solar energy appears promising in view of the ways that solar power has developed over the past decade. Global solar energy production was over 90 terrawatt hours (TWh) in 2012, compared to less than 2 TWh for 2003. (Wilson, 2013)

Between the 1950s and 1970s, photovoltaics had mainly been used in spacecraft. It was the oil crisis of 1973 that encouraged researchers to investigate new ways to produce more sustainable energy, which gave rise, for example, to the ‘Sunshine Program’ in Japan. Similar programs were also started in Europe, initially in Germany, but later also in other sunny European countries. The global photovoltaic market forecast, known as ‘Solar Generation’, which first appeared in 2001 founded by Greenpeace and the European Photovoltaic Industry Association (EPIA), has documented the steady global increase in the use of photovoltaics. The increase in electricity prices and the decrease in the cost of photovoltaics are considered as the two main reasons for the expansion, together with society’s increased environmental awareness. The 2013 ‘Solar Generation report’ stated that photovoltaics are, for a second successive year, the most installed new electricity source in Europe. In 2013, Germany demonstrated the largest increase in photovoltaic installation in the world, with 7.6 gigawatts (GW) of newly connected systems, followed by China, Italy, USA and Japan. At that point in time, these five countries accounted for two-thirds of the global market. (Green, 2004, p.23; Hamakawa, 2004, p.235; Cameron et al., 2006, p.3-6; Masson et al., 2013, p.5-6) In 2010-2011, the EPIA predicted that the countries of

the Sunbelt (within $\pm 35^\circ$ latitude around the equator) hold the potential to provide a major part of their energy requirements from photovoltaics by 2030, provided that the potential within the region can be ‘unlocked’. These countries contain 75% of the world’s population and provide 40% of the global electricity demand. On this basis, the EPIA studies suggested three possible ‘deployment scenarios’ to help to unlock such potential; baseline, accelerated and paradigm shift. This would provide potential, depending on the scenario, to reach an installed photovoltaic capacity within the region of up to 1100GW by 2030. It is estimated that photovoltaic solar energy could constitute 12% of the total power generation within some of the Sunbelt countries by 2030. (Stuart, 2010; Kearney et al., 2011, pp.6-7)

2.3.2 *The development of the efficiency and lowering of cost levels of photovoltaics*

Photovoltaic cells essentially convert photons into electrons, so sunlight can be converted into electricity. A traditional solar cell consists of two layers of semiconductor, one positive (p-type) and one negative (n-type), between which electrons move. Voltage is created via freed electrons, through light absorption. The dark colour of the background layer of the cell is required to maximise the light absorption. The top layer is normally transparent, to allow as much light as possible to be absorbed into the cell. The power supplied by the photovoltaic is a function of the electrical current and voltage generated. The cells can be connected either in parallel or in series. A photovoltaic cell generates direct current (DC), which has to be converted into alternating current (AC), when required for industrial or domestic use. No cell can operate at 100% efficiency, due to unavoidable energy losses, for example through thermal energy. The level of current output is primarily area-sensitive; the larger the area of the cells exposed to the sunlight the more current is produced. The resistance in the circuit through which the electrical current flows is another important factor determining the efficiency level of the cells. (Smith, 2001, p.37; Pagliaro, Palmisano and Ciriminna, 2008, p.31; Wilson, 2012, p.41; Power Textiles Limited, n.d.)

The efficiency level of today’s commercial photovoltaics is close to a maximum of 20%, and slightly less for commercial thin films. (Belán, 2013) In the laboratory, however, photovoltaics have demonstrated markedly higher results. In 2008 Green and Wenham were the first to reach an efficiency level of 25% in a laboratory environment. At the time, this was thought to be close to the limit of theoretical efficiency of photovoltaics,

which was estimated to be 26-29%. (Science Daily, 2008) However, the predictions of the theoretical efficiency limit of cells have had to be re-evaluated as the research into photovoltaics has progressed. The theoretical limit proposed in 2008 was dramatically increased in 2013, due to breakthrough results presented by the Fraunhofer Institute for Solar Energy Systems ISE, Soitec, CEA-Leti and the Helmholtz Centre Berlin. Their new concentrator photovoltaics (CPV) had shown an efficiency of 44.7% and were claimed to achieve more than twice the efficiency of conventional photovoltaics. (Fraunhofer ISE, 2013) Another 2013 breakthrough in efficiency levels for photovoltaics was achieved by North Carolina State University and the Chinese Academy of Science. This team presented a new, low cost photovoltaic (using the polymer PBT-OP), with an efficiency of 36%, much better than that produced using similar previously established polymers. The PBT-OP cells demonstrated an open circuit voltage (the voltage available from the photovoltaic) at 0.78 volts, which can be compared to an average of around 0.6 volts for other comparable polymer cells. (Zhang et al., 2013)

The first photovoltaic cells, 'the first generation silicon-wafer based cell', which at the time were considered to provide good efficiency, needed large amounts of crystalline silicon in the construction. Over 40% of the total production cost was attributed to the material cost of the silicon. (Green, 2004, p.24 and 2006, p.12-13) 'The second generation solar cells' were developed as an alternative to address the increasing shortage of silicon within Europe at the time. The cells were based on thin films which were less expensive to produce, due largely to the decreased use of silicon, compared to the first generation cells. At the time, thin film photovoltaic cells were considered as a cost-effective alternative, but it was still questionable whether the cells would be low enough in cost for the energy market. However, these second generation cells proved to be less efficient than the first generation cells. (Bagnell and Boreland 2008, pp.4390-4392; Jayawarden et al., 2013) The second generation thin films consisted of both glass-based rigid and more flexible alternatives. (Derbyshire, 2006, pp.7-8) As the name implies, the latter type of photovoltaics offered the advantages over rigid cells of being more flexible in use. They are also stated to be easier to customise and to integrate into applications, as well as being thin, lightweight and more environmentally friendly. (Pagliaro, Palmisano and Ciriminna, 2008, pp.12-13; Jayawarden et al., 2013)

The next step in the development was ‘third generation solar cells’. These combined the advantages of the two prior generations to obtain cells that were more efficient in terms of cost and power (price/watt). The development of the third generation cells has focused on a variety of different technical approaches in advancing the design of the cell and its components, resulting in low cost, high efficiency cells. (Green, 2006, p.4-5; Brown and Wu, 2009, pp.394-395; Jayawarden et al., 2013; Lind, 2013, p.10) The research into the third generation cells also includes the dye sensitised solar cells (DSSC), which operate at lower light levels compared to more traditional photovoltaic cells. (Pagliaro, Palmisano and Ciriminna, 2008, p.11) In 1991, Grätzel and O’Regan published results of the first more efficient DSSC cells. (O’Regan and Grätzel, 1991) These cell constructions have later been named ‘Grätzel cells’. (Wilson, 2012, p.44) Further improvements of DSSC cells have resulted in the current efficiency level of 12%. (Heo et al., 2013) The dye-sensitised cells work essentially by imitating the process of photosynthesis (the way plants convert sunlight to energy), in which the organic layer (the dye) in the photovoltaic represents the chlorophyll in the plants. The cells use a simple and low cost manufacturing process and are environmentally friendly. (Jasim, 2011) Dye-based photovoltaics can be produced in different colours depending on aesthetic demands. (Pagliaro, Palmisano and Ciriminna, 2008, p.15) In 2008, Wingfield, designer and owner of Loop.pH, arranged ‘Solar Jam workshops’ in London to demonstrate the simplicity of the material, claiming that everyone can make their own solar cell in their kitchen. (Loop.pH, 2008)

The 2013 findings and developments by Ravi Silva (Advanced Technology Institute at the University of Surrey) encompassing photovoltaics and nanotechnology have resulted in an outline of the next group proposed as ‘the fourth generation of photovoltaics’. These new materials provide improved efficiency, beyond that of previous photovoltaics, through incorporation of active inorganic nanomaterials within the solar cells. (Beliatis, 2013; Jayawarden et al., 2013; La, 2013)

The average module cost of a silicon wafers was calculated as \$100/watt in 1975. (Pagliaro, Palmisano and Ciriminna, 2008, p.4) The cost has dramatically reduced since then. (Parkinson, 2013) However, it is difficult to provide exact year-by-year cost data of the historical price reduction of photovoltaics, due to conflicting available data within the pricing system of photovoltaics, as stated by Fledman et al. (2012). In addition, Jones (2013) states that a paradigm shift is presently occurring within the

photovoltaic price market, for the period 2007-2011 when the price of one single crystalline silicon module (such as the Chinese Tier 1) was used to represent the entire global market price. In the period 2012-2016, this price setting no longer appears to be appropriate. Jones argues that the paradigm shift arises from the change within the percentage of globally installed photovoltaics, in particular the recent increases in installation in China, Japan and USA as well as unique price drivers that have given rise to regional price variations. The outcome of the paradigm shift is resulting in a geographical variation in industry prices. The module pricing for Tier 1 Chinese modules differed, in the 4th quarter of 2013 by 35% from \$0.56/W in Latin America to \$0.80/W in Japan. (Jones, 2013) The average costs for vertically integrated ‘Tier 1’ crystalline silicon wafers were, according to the NPD Solarbuzz’s ‘Polysilicon and Wafer Supply Chain Quarterly report’ for 2013, just above \$0.20/watt and were predicted to be just under that for 2014. Prices are forecast to fall due to an existing severe oversupply and the extremely low selling prices in the polysilicon and the wafer photovoltaic market. Charles Annis (vice president at NPD Solarbuzz) predicts that the prices will fall to “previously assumed impossible levels”. (Solarbuzz, 2013)

2.3.3 *Photovoltaics integrated into textiles*

In design, there has been a great interest in photovoltaics, from architects, through building constructors as well as from industrial, product, fashion and textile designers, involving, for example, integration with textiles and electronics. (Schubert and Werner, 2006; Pagliaro, Palmisano and Ciriminna, 2008, pp.17-18; Seymour, 2008, p.22) This section gives an overview, using a selection of examples, where mainly flexible, but also printed, photovoltaics have been integrated in textiles.

Research into photovoltaics integrated in textiles has been proceeding for some time. Product development of portable objects powered by photovoltaics focused initially on calculators, alarm clocks and air purifiers. (Hochman, 2009) However, research has also started to include new applications, such as organic photovoltaics incorporated into *wearable technology*, for example garments or bags that can power an iPod or a computer battery. (Schubert and Werner, 2006; Seymour, 2008, p.21) As early as 1995, Philips Design presented their ‘Vision of the Future, Music T-Shirts and Solar-Energy Recharge Jacket’, conceptual garments using wearable technology with photovoltaics as the power generators. (Marzano, 1999) A more design-led set of garment prototypes with integrated photovoltaics has been reported since 2000, with an

increased number of samples presented at branch fairs and exhibitions. (Schubert and Werner, 2006) The backpack with incorporated solar cells from the 'H2 Series', from 2005-2006 by O'Neill was reported to be the first product on the market that could be used as a portable charger. (Miles, 2005) In 2009, the Italian brand Ermenegildo Zegna launched a second version of their photovoltaic jacket, the 'Ecotech Solar Jacket'. They had been the first to introduce a top brand solar jacket (the Solar JKT), having launched the first version two years before. (Talk2myShirt, 2009) In 2008, Voltaic launched a laptop bag 'the Generator', which could recharge a battery of a conventional laptop during a full day of sun. (Seymour, 2008, p.189) In 2007, Schneider constructed 'Solar bikini', Figure 2.45, a two-piece costume consisting of 1' x 4' flexible solar cell films stitched onto the fabric with conductive threads. The garment was capable of creating a 6.5 volts charge, and was equipped with a USB port for the iPod. (Schneider, 2007)



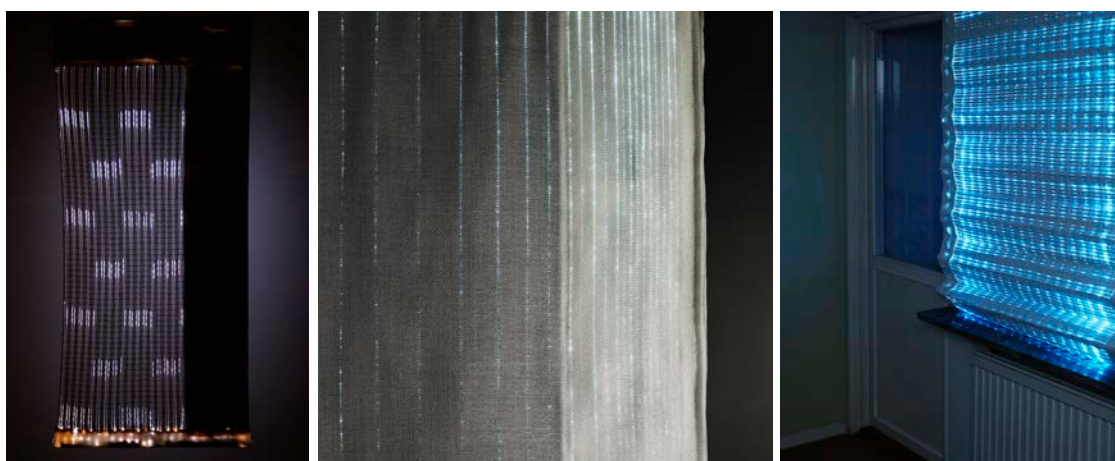
Figure 2.45 (left) The 'Solar bikini', 2007, by Schneider, which can charge an iPod during a full sunny day. (Schneider, 2007) Figure 2.46 (right) The 'Day-for-Night' dress, consisting of 444 white circuits by Studio 5050. (Seymour, 2008, p.115)

The market has also produced more artistic fashion pieces, such as the 'Day-for-Night' dress by Studio 5050, Figure 2.46, from 2006. The dress consists of 444 white circuit boards, all connected to control the incorporated LEDs. The system is powered from solar cells, which are incorporated in the design. The dress is built up as a modular system with regard to hardware as well as software, so the number of circuit boards can be changed, as the dress is made shorter or longer. (Studio 5050, 2006)

Examples of more recent products are the dress and coat concept 'Wearable Solar' by fashion designer van Dongen. The garments, presented at the 2013 'Wearable Future' conference, were constructed in collaboration with Holland and Jongerden. The

coat contains 48 rigid cells and the dress 72 flexible cells, that each can charge an average smartphone by 50% within one hour of full sunlight exposure. (Van Dongen, 2013) Another example is the colour changing conceptual ‘Mood Wear’ garments by designer Yang, Heriot-Watt University. The fabrics, incorporating sensor-control, woven with luminescent materials that are intended to reflect the wearer’s mood, are powered through integrated flexible photovoltaics. (Stylios and Yang, 2012)

The wearable technology market has had to deal with several issues through the development of the products, such as the stiffness of the flexible photovoltaics in relation to the highly flexible woven textiles, the need for washable cells, together with satisfying both the practical and aesthetic requirements for a seamless integration of electronics and photovoltaics. (Schubert and Werner, 2006, p.43) Some of these issues have still not been resolved satisfactorily. The thinner flexible cells, such as the Si-thin film cell, have performed quite well in terms of integration. The printed DSSC cells have also shown good potential for integration. (Schubert and Werner, 2006, p.44)



Figures 2.47-2.49 ‘Energy Curtain’ a woven window shade with solar cells and optical fibres, creating a self-powering light shading and light emitting system, by Interactive Institute and Müller. (Interactive Institute, n.d.b)

Research into incorporated photovoltaics has also been conducted for the interior textiles market, for example conceptual prototypes for curtains. ‘The Energy Curtain’, Figures 2.47-2.49, a woven window shade created by the Interactive Institute in Sweden in collaboration with Müller, is such an example. The textile was constructed using light-emitting optical fibres and photovoltaics. The energy harvested from the sun during the day was stored to power a light-sensitive, controlled design within the curtain when it was dark, thus creating a self-powering energy system. The amount of energy

output was regulated by how far down the user pulled the curtain during daytime. In the same way, the amount of light spread, within the design, could be controlled in the evening. The curtain allows the user to actively choose between the use of sunlight during day and the energy storage for illuminating possibilities in the evening. The curtain was said to evoke awareness of the local sustainable system, and the user's behaviour towards energy over time. (Ernevi et al., 2005b)

'Soft House', Figures 2.50-2.51, by Kennedy, is another conceptual example of interior window textiles with integrated photovoltaics. The project displays a futuristic scenario where machines and electrical devices used within the home are powered using the energy harvested by the hi-tech window curtains. The textiles are constructed from organic photovoltaics, providing the solar cell with a more flexible structure. (Chapa, 2008) The curtains are designed to move so that they follow the sun during the day. It was calculated that the textiles would be able to generate up to 16 Kwatt-hours of electricity, which was more than half of the daily power needs of an average American household (at that time). (Wright, 2008)



Figures 2.50-2.51 The concept 'Soft House' by Kennedy, harvesting solar energy through woven solar cell curtains, for powering the electronics within the house. (Chapa, 2008)

Another form of sun-screening object with integrated photovoltaics is found in Corchero's 'Solar Vintage' project, Figures 2.52-2.53, a collection of fashion accessories that explore the functional and aesthetic qualities of thin photovoltaic cells. (Collet, 2007, p.17) Corchero has designed artefacts, such as jewellery and a solar parasol, which during the day harvest solar energy, so that by night they can light up the LEDs within the textile structure. Corchero aimed to create new values for almost forgotten objects, to give them a place again within society. For example, the parasol by night, in her words, becomes a 'shining chandelier'. (Corchero, 2010) The electronics and the photovoltaics are visibly integrated as an aesthetic element in the design. The conductive threads are

embroidered into the textile. The jewellery items are equipped with organic flexible solar cells (non-silicon based). (Seymour, 2008, p.46)



Figures 2.52-2.53 Corchero's 'Solar Vintage' collection, solar umbrella (right) and solar fan (left). (Corchero, 2010)

Additionally, research has focused on improving the application of solar technology by printing or using a plasma unit to apply photovoltaics onto textile substrates. Over the last few years, there has been increased research into the flexibility that can be achieved through printed structures, such as printed photovoltaics and printed electronics. Harrop, founder and chairman of IDTechEx, predicted an increased interest over the forthcoming ten years in this field. (Harrop, 2009c) Wilson and Mather at Solar Textile in collaboration with Heriot-Watt University is an example of research in creating more flexible textile structures with incorporated photovoltaics by using a plasma unit. (Wilson, 2012) Krebs et al. (2005), at RISØ DTU, the National Laboratory for Sustainable Energy in Denmark, is an example of a research team working with printing the photovoltaics. Conceptual design applications, with screen-printed photovoltaics, were presented in 2009 through collaboration between RISØ DTU and the Danish Design School. Two design students, Hertz and Langberg, each designed fashion garments, which partly consisted of RISØ DTU's patterned polymer photovoltaic by incorporating the PET substrate into the design. The connection between the different cells was created using copper wires within the garments. The solar cells were screen-printed in 30 x 45cm pieces (see Figure 2.54), which were used to create a module-based design that provided flexibility even in the larger printed area of the garments. Hertz created a number of garments (see Figures 2.55-2.57) that acted to provide power for light sources. (Krebs et al., 2005; Henderson, 2009; RISØ DTU, n.d.b and n.d.c)



Figure 2.54 (left) Detail of photovoltaic printed onto textile, by RISØ DTU. Figures 2.55-2.57 (centre and right) ‘Element-ary’, garments with incorporated photovoltaics, by Hertz, in collaboration with RISØ DTU. (RISØ DTU, n.d.c)

Wingfield and ‘Nobel Textiles’ established a further collaboration between RISØ DTU and a designer through one of the two versions of the ‘Metabolic Media’ project. The photovoltaic concept (see Figures 2.58-2.59) took its starting point from the 1997 Nobel Prize for Chemistry winner Sir John E. Walker’s discovery of the biological process of how enzymes within humans lead to the formation of ATP (adenosine triphosphate). Wingfield and Loop.pH created a lightweight self-standing textile construction that became a base for growing plants (such as blackberries) without the use of soil. The first version of the concept incorporated dye-sensitised photovoltaics, which could be constructed using the berries that were cultivated on the textile structures. The harvested energy from the dye-sensitised photovoltaic was considered to operate a feeding and monitoring system for the plants growing on the textile construction. The scenario was perceived to create a continuous closed cyclical system. The second version of ‘Metabolic Media’ presented a solution with a polymer solar cell from RISØ DTU incorporated in the textile construction, rather than using the dye-sensitised photovoltaic. (Loop.pH, 2008; Wingfield and Walker, 2008)



Figures 2.58-2.59 the Nobel Textiles project ‘Metabolic Media’, by Wingfield and Loop.pH, with solar cells from RISØ DTU.

Research is also presently being conducted to investigate the possibility of fibre-based photovoltaic yarns, for example by extrusion. Experiments to create such cells have been carried out using polycrystalline silicon, dye-sensitized titanium dioxide, and polymers, as well as fibre-based organic photovoltaic cells (OPV). (Shtein, 2008) The Technical University of Eindhoven is currently conducting such research, and presented a proof of concept with a prototype at the Smart Textile Salon in 2013. Their current prototype uses woven glass fibres to lead the light into small diodes with photovoltaics. The prediction of the research group, in 2013, was to have a commercial thread available after 5 years. The laboratory thread is produced as a 5mm fibre that is later extruded to 100µm. (Ashford, 2013)

2.4 The principles of shadows

Shadows influence the perception of the surroundings. (Cheng and Kieferle, 2011, p.54) A shadow can be described as a darker area created by an opaque object on the opposite side from its illuminating source. The illuminating source and effect of the shadows helps us to identify an object. (Gombrich, 1995, p.6) A moving shadow generally attracts the attention of the eye more easily than static ones. The movement creates a relationship between the light source, the object and the surface with the projected shadow. (Cheng and Kieferle, 2011, p.54)

Baxandall (1995) defines a shadow through the specification of three different shadow types, *self-shadow*, *slant/tilt shading* and *projected shadow*. Baxandall derived these definitions as an alternative to the more common definitions at the time, *the attached shadow*, *the shading* and *the cast shadow*, as he thought there were partial contradictions in the terminology (see Figure 2.60). The attached shadow is the shadow created by the body of the illuminated object, the area that is facing away from the illumination source. This creates apparent volume in the viewed object. The shading receives a varied amount of light, due to small angle differences in the shaded object. The cast shadow is the darker surfaces that are cast from the illuminated object onto nearby areas or onto the object itself. The cast shadow is, apart from being created by the shape and angles of the illuminated object, also affected by the surroundings it falls upon. This shadow type describes the position of the object within a space. (Baxandall, 1995, pp.2-4)

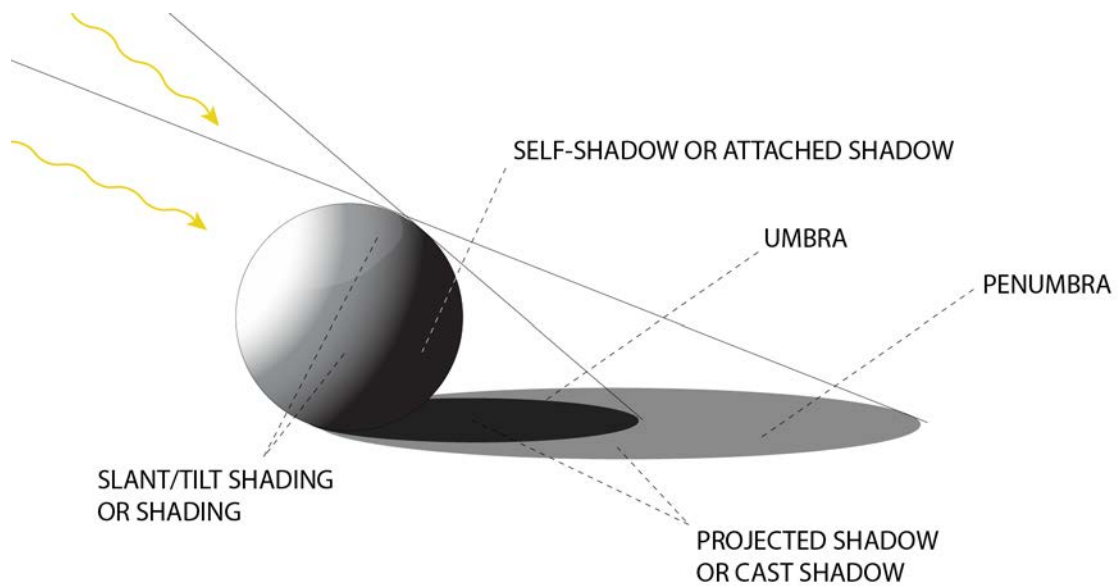


Figure 2.60 Graphic demonstrating the different shadow types.

A shadow reflected onto a downward-angled surface looks longer and a shadow on an upwards-angled surface looks shorter, than a shadow on a horizontal even surface. (Gombrich, 1995, p.13) The shadow differs depending on the qualities and properties of the light, such as intensity, direction and distance, as well as how a material transmits, reflects or refracts light. (Cheng and Kieferle, 2011, p.54) The conditions of the shadow will differ depending on whether the source is natural or artificial. Light sources can range from point sources, creating sharp edged shadows, through wider sources that create smooth, gradient edges, and to the perfect ambient light (a non-directional source) with no shadow at all. The plane source, such as the sun, casts an umbra (Latin for shadow - the area that is darkest lit, where the illuminating source cannot reach) as well as a penumbra (Latin for a semi-shadow - the area that is in half-shadow) (see Figure 2.60). (Baxandall, 1995, p.5) The shadow is affected by the direction of the illumination and the intensity of the light source. A strong light directed straight downwards (noon sun) creates a dark and truncated shadow with sharp detailing on the surface. A weak and low angled light (dusk or dawn) creates a longer and more gradual shadow. (Anderson Feisner, 2000, p.105) The cast shadow is likely to be darker than the attached shadow, due to the fact that the umbra normally does not face the illuminating source, but rather the attached shadow. (Baxandall, 1995, p.15)

The material that the light travels through (for example the atmosphere) also affects the quality of the light source and, indirectly, the shadow, involving effects such

as diffusion. Another phenomenon that Baxandell discusses is ‘the global illumination’, the additional light bouncing from the object’s environment creating an impact on the lit object. (Baxandall, 1995, pp.5-6)

A shadow created by the texture of the illuminated object, the small darker areas, helps the viewer to read the construction of the surface. The larger darker and lighter areas inform the viewer about the object. (Gombrich, 1995, p.10) A textile normally would be an anisotropic surface (small scale structures which reflect the light unevenly, more in some directions than others) creating micro-shadows on the surface. The opposite is an isotropic surface, which creates an even reflection all around the object. (Baxandall, 1995, p.8)

Impressionist artists, such as Monet, studied the colour of light and shadow through their paintings, with a foundation from the principles of colour physics. (Pipes, 2003, p.147) Monet completed several paintings of the same object and scenery, such as haystacks, Rouen Cathedral, the Thames of London and the Seine, at different times of the day, from early dawn to late dusk, as well as in varying seasons of the year (see examples of the Grainstack in Figures 2.61-2.62). Monet’s use of colour becomes a documentary record of the perception of the differences in the colours and nuance of the shadows in relation to the illuminating light. (Hayes Tucker, 1989, pp.101-102, 167, 233, 256-262) The colour of the shadow is related to the wavelengths of the spectrum of the illumination source. (Gombrich, 1995, p.10) The shadow demonstrates the colour of the complementary colour of the illuminated object as well as the complementary colour of the illuminating source. (Anderson Feisner, 2000, p.104) According to Birren, shaded areas and coloured surfaces that are projected with lower illuminated lighting appear to shift in hue towards violet. (Birren, 1987, p.36)



Figure 2.61 (left) ‘Grainstack’ (thaw, sunset) 1890-91, private collection, England and Figure 2.62 (right) ‘Grainstack’ (snow effect) 1890-91, Museum of Fine Arts, Boston. (Hayes Tucker, 1989, pp.97-98)

Chapter 3 Methodology

This chapter covers the methods used during the practice-based research that has led to this thesis. The chapter includes an overview of the methods used (section 3.1), as well as more detailed descriptions of specific methods and descriptions of the terminology, materials and technologies used.

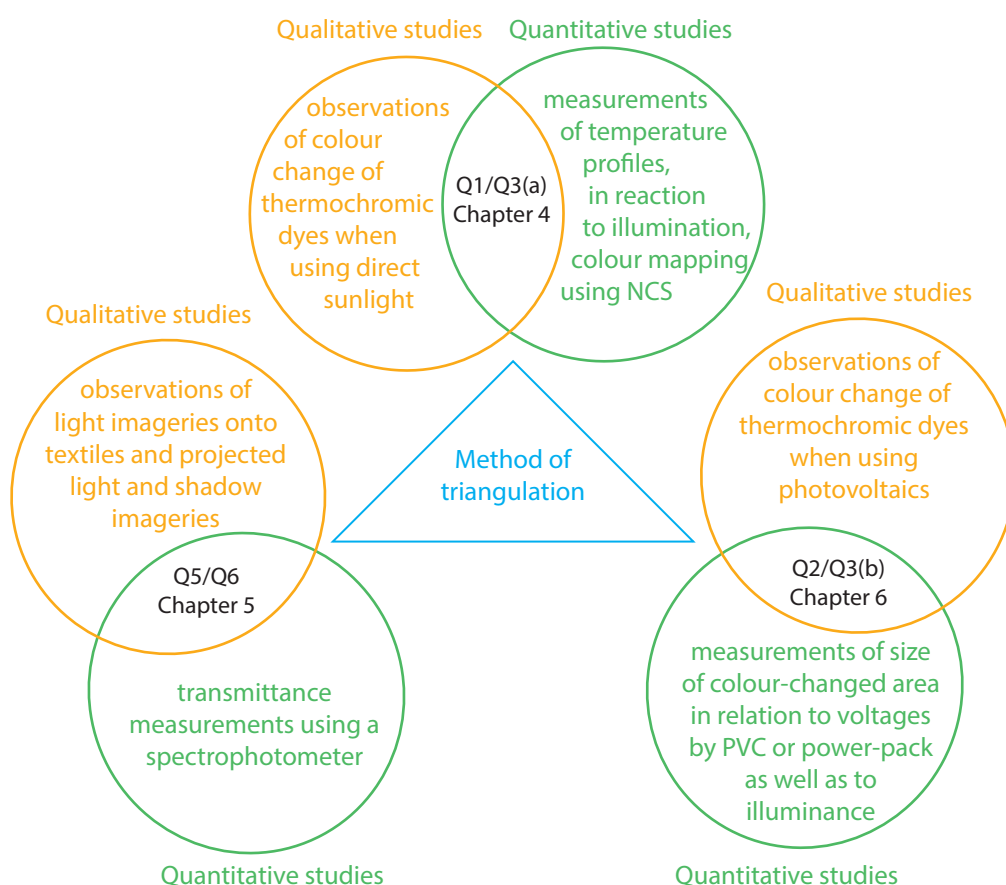
This chapter begins by outlining the design approach using, primarily, design related research methods. The author's prior tacit artistic and print design related knowledge has provided the foundation for the use of the method of *participatory research*. Section 3.1 in the chapter provides information on how the design brief, in the form of a conceptual framework, was devised to evaluate the findings of the design process, carried out by the author in the role of the textile printmaker practitioner. The work of this thesis was primarily built on an extensive set of observations as described in section 3.7 *Observation methods*. The visual observations, described in section 3.7, and using different defined set-ups, referred to as A, A2 and C indoor, as well as B outdoor. These set-ups were constructed in a controlled manner in order to reduce the subjectivity of the observer. Further, section 3.1 describes the use of *reflexivity* as a complementary analysis method, which allows reflection on the author's subjective role within the observations conducted and how this analysis process shaped the outcomes of the research. Within this thesis, all samples were observed during two defined sets of sky conditions (sunny and cloudy), as discussed in section 3.7.1 *Daylight conditions*. These definitions were devised so that the data could be analysed to detect patterns of behaviour associated with the colour change of the thermochromic dye, in either sunny or cloudy sky conditions. The variables that were studied in the course of this analysis, both in sunny and cloudy sky conditions, indoor as well as outdoor, were: textile substrate thickness, colour of the dyes and activation temperatures. The aesthetical investigations of section 5.6, described in terms of method in section 3.7.4 *Light observations within a scaled model*, were carried out using two set-ups, defined as set-ups D and E. The scaled model used was based on a conceptual scenario of a street in Seville, Spain. The street was assembled so that it contained sun-screening textiles (sun-sails), which were constructed from black as well as white paper with laser-cut designs. The model also allowed variation of the incident light sources. Section 3.9 *Methods used in the collaborative study*, details how some parts of these investigations were carried out in a collaborative manner, based on the conceptual scenario of a street in Seville.

This chapter also describes how the author, in specific situations, chose to reinforce the findings of certain lines of enquiry using a scientific, often quantitative, approach. In this way, the subjective nature of the participatory research was cross-referenced using a more objective perspective. For example, the investigations conducted as described in chapter 6 were based, as defined in section 3.11 *Methods for investigating the capacity of solar cells to power the heating mechanism for the printed thermochromic leuco dyes*, on using actual sunlight, referred to as set-up J (outdoors), as well as a situation in which sunlight was simulated using a specially-constructed light box fitted with two 240V halogen lamps that simulated sunlight, referred to as set-up I (indoors). Observations were also made on the textile samples, printed with thermochromic dyes, investigated with these set-ups during the two pre-defined daylight conditions (sunny and cloudy sky). Other quantitative approaches used within the work of this thesis were measurements carried out with a spectrophotometer to create light transmittance (%T) curves in order to assess the light transmission properties in certain samples, outlined in section 3.10 *Light transmittance method*, as well as measurements of temperature curves using a hand held thermometer probe, used where it was judged important to establish the temperature profile, as outlined in section 3.11.

3.1 Overview of methods

This thesis is based on a *practice-based research* approach using, primarily, research methods for the creative industries. (Collins, 2010, Niedderer & Reilly, 2010) The author's prior tacit artistic and design related knowledge and experience in print design processes and aesthetic effects have provided the foundation for the formulation and definition of the guidelines. These guidelines have been established to expand the aesthetic vocabulary for designers to facilitate dealing with the complexity of the design process when working with textiles printed with thermochromic leuco dyes. These are applicable for sun penetrating and/or sun activated textiles printed with thermochromic dyes. This experiential and tacit knowledge, which has also been referred to as 'knowing – in – action' and 'reflection in action' (Schön, 1991, p.49), or 'the design mode of expression' as defined by Archer in 1979, is used as 'organized inquiry towards communicable as well as generalizable and transferable results', placing and testing this personal knowledge in an academic framework. (Niedderer & Reilly, 2010) The author, therefore, takes the role of both the researcher and the textile printmaker practitioner through *participatory research*. The approach to the research is mirrored

by Bergold and Thomas (2012) as ‘geared towards planning and conducting the research process with those people whose life-world and meaningful actions are under study’. The researcher has observed her own responses with the aim to expand the aesthetic vocabulary for designers within the textile printmaker practitioners’ design process, when the sun acts as either a direct or an indirect activator of sun-screening textiles printed with thermochromic leuco dyes, as presented in section 1.2. (Schön, 1983/1991, p.49) The approach developed is tested against theories and approaches reported in literature, which have been considered and integrated with the author’s practice directed process. The author has used prior knowledge of established general print design processes, alongside established knowledge, to enable comparisons to be made and to provide the foundation for the formulation and definition of new guidelines for designers applicable for sun penetrating and/or sun activated textiles printed with thermochromic dyes.



Graphic 3.1 Outline of how the method of triangulations links the different investigations.

The research employs *triangulation*, through the practice of both *quantitative* and *qualitative* methods, to validate the information discussed. The knowledge gained was

drawn from both design methods using quantitative studies (see orange circles, Graphic 3.1), as well as from a more scientific approach using quantitative studies (see green circles, Graphic 3.1), reflecting the multidisciplinary nature of the research. (Polanyi, 1966; Olsen, 2004; Bergold and Thomas 2012) The author chose to re-evaluate the findings of certain experiments using the scientific (quantitative) approach. Due to the subjective nature of the participatory research, it was considered beneficial to cross-reference results from a more objective perspective, where appropriate.

A qualitative study is reported, applied to addressing research questions Q1 and Q3 (a) (see section 1.3), in which the use of the heat of the sun as an activator of thermochromic textile designs is studied. Qualitative studies through observations were also used to answer research questions Q2 and Q3 (b) as well as Q5 and Q6. The observations, for Q2 and Q3 (b), were based on either activation or lack of activation of samples printed with thermochromic dyes (i.e., colour change or no colour change), in relation to the effects of different conditions of illumination involving sunlight and artificial light. The observations, for Q5 and Q6, were based on movements and changes within projected light and shadow imageries, due the effects of different sunlight and artificial light illumination conditions, different translucency levels and the effects of cut out shapes within the printed substrate material. The qualitative data obtained includes information about possibilities of the textile printmaker practitioner's in controlling the aesthetic outcome and the processes that are essential for creating sun-screening textiles printed with thermochromic dyes. These data were then used for further investigation within the practitioner's design process. The effects thus observed from the use of the heat from the sun as a direct activator of thermochromic textiles, are further discussed in relation to established design methods in general use by printmaker practitioners. The results of the investigations carried out within this thesis are compared with those obtained using 'traditional' electrical heating mechanisms and, at times, from body heat. The definition of 'traditional', in this case, refers to such heating mechanisms, as discussed in section 2.1.5, which cannot directly be powered by renewable energy sources. The qualitative data, collected through observations, were documented by analytical annotation, namely field and laboratory notes, photographs and film. (Collins, 2010, pp.48-53 and 168-171; Madrigal and McClain, 2012)

Quantitative studies were additionally used to address research questions Q1 and Q3 (a), Q2 and Q3 (b) as well as Q5 and Q6. Quantitative measurements, establishing

curves describing the temperature profiles for activation of colour change and time intervals of activation of the printed thermochromic dyes in relation to conditions of illumination and lux values, were conducted to discuss research questions Q1 and Q3 (a). Quantitative definitions, through colour mapping using the Natural Colour System (NCS), relating to research questions Q1 and Q3 (a) were additionally conducted to compare the colour outcomes from thermochromic dyes from different suppliers and with different activation temperatures. Quantitative measurements were further conducted to discuss research questions Q2 and Q3 (b), based on a study of the colour change effects in the leuco dye printed samples, in relation to electrical currents generated by solar cells and the lux values of the illumination. The data were obtained and applied in relation to a number of sets of heating mechanisms and illumination sources (natural and artificial). Quantitative measurements were also conducted, to answer research questions Q5 and Q6, to provide transmittance values from the devoré-printed and laser-treated textile substrates, using a spectrophotometer. The quantitative data was, in this case, used in order to formulate guidelines for creating design solutions involving thermochromic dyes applied to textiles, which are translucent in certain areas. (Collins, 2010, pp.48-53 and 172-177; Madrigal and McClain, 2012)

Both the qualitative and quantitative studies were based on the method of *sampling*, meaning that the material studied consists of a selection of samples and investigated parameters. (Collins, 2010, pp.178-179) The number of samples chosen is defined alongside the definition and documentation of each individual study conducted. The analysis of the research described is based on data collected from *multiple sources*. (Collins, 2010, p.49) These data include observations of actual fabric samples and the range of procedures used to produce the variety of textile outcomes throughout the thesis. It also includes the field and laboratory annotation of observations, which is both analytical and reflective, and also utilises visual data (photographs and films). Quantitative measurements of colours, temperatures, electrical current and light-transmittance values are recorded, facilitated by dialogue with relevant researchers from engineering and physical sciences disciplines. Selected observations were documented in real time using photography and video to supplement the researcher's observations, allowing a more objective review of the design process at a later stage. *Reflexivity* was used as a complementary analysis method in order to allow reflection on the author's

subjective role within the observations and how this shaped the outcome of the research. (Schön, 1983/1991, p.49; Collins, 2010, p.169)

The thesis describes a number of studies and in-depth experiments that contain a triangulation of different research methods, with three main studies being of note. Firstly, the conceptual framework acts as a general methodological approach leading all of the work within this thesis. In this, a *design brief* is addressed using established textile print design processes that are applied and modified as required in reflexive response to observations. The conceptual framework was created in order to investigate the following: to define the influence of sunlight on the textile printmaker practitioners' design process when sunlight is used as an activator for thermochromic dyes. This overall approach examines a specific set of events involved in the different creative development stages within the textile print design processes. The general textile print design process has been defined, in this thesis, through the following stages: the brief, contextual research/sourcing ideas, the aesthetic design development, the analysis of colour, the evaluation of samples and the final textile outcomes. The study allowed a comparative analysis of this particular textile print design process against established textile print design processes. In this way, the author was able to evaluate the findings (the differences and similarities within the processes) and to formulate and implement new guidelines to expand the aesthetic vocabulary for designers. The aim was to facilitate dealing with the complexity of the design process when working with textiles using thermochromic leuco dyes, especially when integrating thermochromic dyes with solar technology. The overall study has resulted in a comprehensive understanding of the effects achievable when using the sun to activate thermochromic dyes.

Secondly, a distinct study (see sections 5.6-5.7), based on a *scenario* set in a street in Seville, Spain, was conducted as a collaborative project with Barbara Jansen, PhD student, Swedish School of Textile and Design, University of Borås, Sweden. (Collins, 2010, pp.154-155) This study focuses on a partially-defined timeframe within the sun's annual path, with an emphasis on the 21st of June. The study provided specific information relating to the changes in light and shadow patterns affected by the sun's path.

A third study was constructed as a *future scenario*, aimed to answer research question Q4, through 'highlighting central elements of a possible future by focusing on the key factors that will drive future developments', as defined by Kosow and Gaßner (2008, p.1). This scenario provides informed speculation on the future potential to use

solar energy, harvested via photovoltaic cells incorporated in textiles, to power heating circuits that activate textile applications using thermochromic dyes. (Kosow and Gaßner, 2008; Collins, 2010, pp.154-155)

3.2 Variables and terminology used

3.2.1 *The textile printmaker practitioner*

As discussed previously, the research reported in this thesis is aimed at established designers as well as design students who work with thermochromic dyes, either currently or in the future. The thesis has a focus on the particular textile technique of print and the designers in question are therefore often referred to as ‘textile printmaker practitioners’. The connotation of the term ‘textile printmaker practitioner’, within this thesis, refers to an individual who is creating textile print designs, the denotation of the term being the person(s) that is physically conducting the design work. Within this research, this included both the conceptual aspects of the design and the physical printing.

3.2.2 *The sun and the sun-screening textile*

This thesis has investigated how the design process used by a textile printmaker practitioner requires to be modified when the *uncontrollable changeable direct activating variable* – the sun – works together with a *dynamic surface variable* – printed thermochromic leuco dyes.

‘Sun-screening textiles’ are used as the conceptual application for the printed thermochromic dyes. The contextual meaning of ‘sun-screening textiles’ refers to textile surfaces, which fully or partly block incoming rays of sunlight towards an individual who is under or behind the textile, with the sun-screen located between the sun and the user.

The sun has both a 24-hour cycle and a 12-month cycle. The individual cycles vary on a day-to-day and year-to-year basis, determined by sky conditions and geographic location on earth. Variables such as the time of sunrise and sunset, hours of sunlight as well as ambient air temperatures are related to the latitude-longitude positions of the location. Since the effect of the sunlight alters, for example due to weather conditions, the sun was defined as ‘an uncontrollable’ and ‘changeable’ variable. It is evidently not possible to program when the sun (the activator) is turned on or off, or to control the amount of heat that is transferred, features that are normally possible to define with sensor-based computer controlled activation systems.

The research was considered from two perspectives: using the sun as either a direct or an indirect heat source for activating thermochromic leuco dyes printed on sun-screening textiles, for both indoor and outdoor applications. The direct heat source involved either heat from the rays of the sun, in contact with a glass window heated by the sun or the influence of the ambient temperature when the sun was shining, or a combination of these effects. The indirect heat source involved harvesting solar energy from the sun, to operate electrical circuitry, and thus to heat the textiles printed with thermochromic dyes.

3.2.3 *Investigated parameters*

The thesis has focused the investigations fundamentally on two pairs of parameters;

(a)



(b)



Figure 3.1 The two pairs of investigated parameters (a) and (b) that are used within this thesis.

The first pair (dynamic and non-dynamic materials), Figure 3.1 (a), consists of thermochromic leuco dyes as the dynamic parameter and ‘permanent’ dyes and pigments as the non-dynamic parameter. There are two phases of the dynamic thermochromic dyes, referred to as ‘colour state 1’, when the dye is inactive (the fabric is cold) and ‘colour state 2’ when the dye is activated (the fabric is heated). ‘Permanent’ dyes and pigments refers to, for example, reactive dyes, metallic or coloured pigments, which do not fit the description of a smart material. They provide a constant effect that does not change by reacting to their surroundings or to external stimuli.

In the second parameter pair (back-illuminated and non-back-illuminated textiles), sun-screening textiles represent the back-illuminated textiles, Figure 3.1 (b). The conceptual sun screening described is simulated by textiles that are either mounted onto windows or hung outside in urban environments. These conceptual textiles are

represented by samples that were printed with thermochromic leuco dyes, sometimes combined with permanent pigments. The non-back-illuminated textiles are defined as printed textiles that are displayed in front of a solid background so that there is no sunlight observed to pass through the fabric.

Four types of applications, see I-IV below, were created for the purposes of an overall investigation of the design processes, described in chapter 7. These comprise combinations of the two pairs of investigated parameters as follows:

- I. A non-back-illuminated textile, printed using only non-dynamic dyes/pigments
- II. A non-back-illuminated textile, printed completely/partially using dynamic dyes
- III. A back-illuminated textile, printed using only non-dynamic dyes/pigments
- IV. A back-illuminated textile, printed completely/partially using dynamic dyes.

3.2.4 *Methods used to define colours*

Observations of the colour change of the textile samples printed with thermochromic dyes were made and evaluated in terms of changes in the colour outcome, as well as the ‘process’ of the colour change (for example the origin and form of ‘heat spread’ and time factors concerning colour change). A change in colour, within the context of this thesis, is defined as a colour that is perceived to have changed in *saturation* (appears more or less saturated), *colour tones* (appears warmer - a hue with more yellow, or colder - a hue with more blue), in *lightness* (either a movement towards more whiteness or towards blackness) and/or in *hue*. ‘Hue’ is defined broadly by the name traditionally given to a particular colour, saturation (colourfulness) by the value of the *chromaticness*, and the lightness as to how dark or light the colour is. The Natural Colour System colour circle is used to define particular hues (black and white are excluded from the NCS colour circle) and the NCS colour triangle to define saturation and lightness. Of the several colour systems that may be used when it comes to specify colours (for example Pantone), the NCS system was chosen on the basis that it is a system often used by designers and architects. The NCS system was found to provide a positive experience for the type of definition of colours that was required within this work. Changes within particular colour outcomes are visualised by plotting in the NCS colour triangle and colour circle, as exemplified in Figures 3.2-3.4.

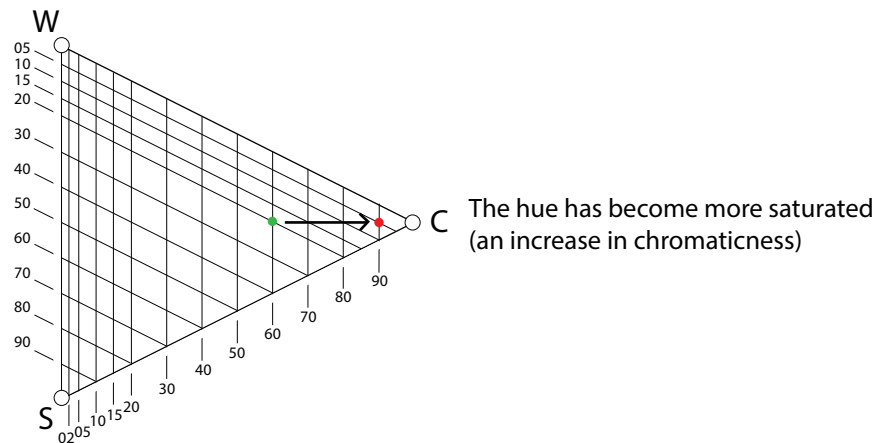


Figure 3.2 Illustration of the NCS triangle visualising the definition of a colour change within the chromaticness (saturation) of the hue. The green and the red circles mark the outcome when a colours change from one state to another.

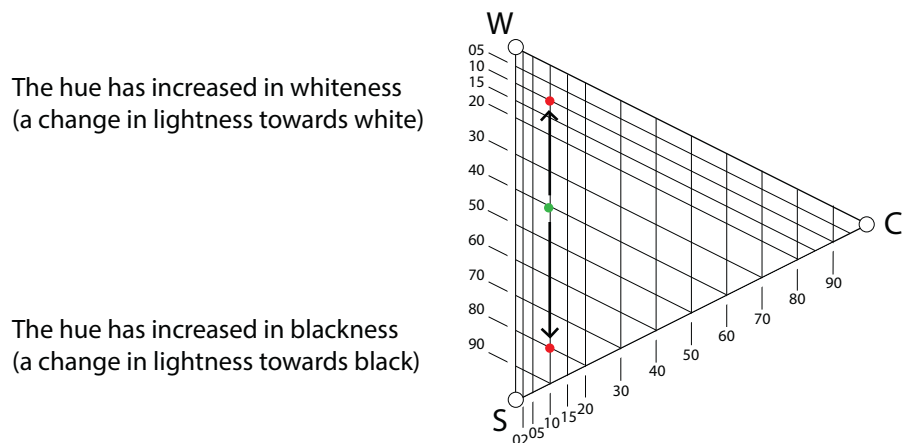


Figure 3.3 Illustration of the NCS triangle visualising the definition of a colour change within the whiteness and blackness (lightness) of the hue. The green and the red circles mark the outcome when a colour changes from one state to another.

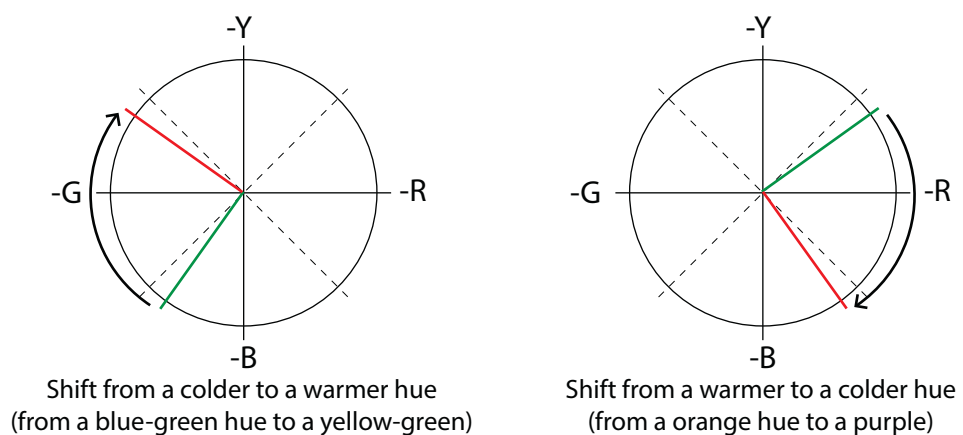


Figure 3.4 Illustration of the NCS circle visualising the definition of a colour change within the tones of the hue. The green and the red lines mark the outcome when a colour changes from one state to another.

3.2.5 *Definition of the focal point*

The focal point is the area of greatest visual importance for the viewer. (Anderson Feisner, 2006, p.172) This feature became of particular interest in relation to colour changes within the design. An area within the expression may, due to the colour change, act as a ‘dynamic space’, by altering between standing out and reverting to within the background of the imagery. (Worbin, 2010, p.266) In this thesis, a shift of the focal point between parts of the elements within the imagery is defined as such an alteration. For example, the focal point might shift from a situation in which there is a balance between all elements within the design towards a main focus only on a specific part of the imagery, as illustrated in Figure 3.5. The focus, within the example, is, more or less balanced between the thinner white lines and the wider grey lines before the colour change, and after the change is rather on the wider, light grey lines and the two thinner white lines.

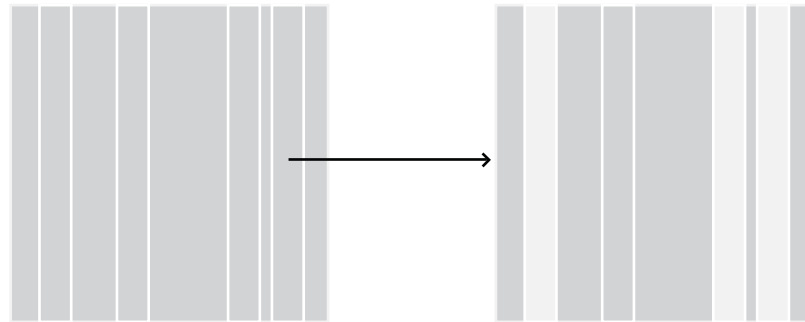


Figure 3.5 Illustration of the definition of a shift of the focal point during a dynamic colour change. The pattern has shifted the focal point from the thin white lines in the left figure to the two thin lines and, partly, the three wide light grey lines in the right figure.

The definition of ‘imagery’, ‘pattern’, ‘design’ or ‘motifs’, which are used synonymously, and to an extent interchangeably, within this research, refers to a composition of a selection of ‘elements’. An element of the design may also be referred to as ‘motif’. The design of the elements may contain various shapes and colours created through treatments of the surface of the textile (such as by print or laser-treatment). The compositions of the designs were constructed either through conscious decisions by the author using self-expression, or by a more random process. Both the elements and the compositions that they make up contain directional as well as non-directional characteristics. A directional element or composition is defined as a shape or design that clearly has a movement towards one or several certain directions, contrasting with non-directional elements or compositions (see Figure 3.6). A

directional element or composition may, further, be unidirectional, bi-directional or multidirectional. (Russell, 2011, pp.70-71; Steed and Stevenson, 2012, pp.123-129)

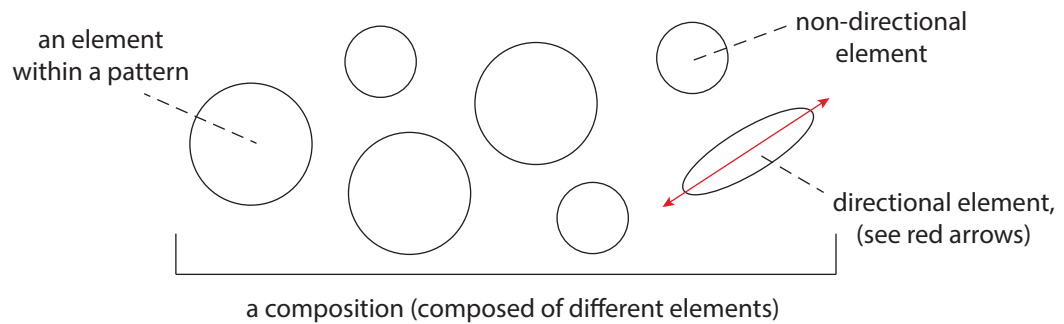


Figure 3.6 Illustration a composition with directional and non-directional elements.

The research deals with both organic and geometric elements. Geometric elements are defined as non-representational. The shapes of these elements are generally basic regular shapes (e.g., the circle, square or triangle) that have quite a low complexity level. However, a composition constructed using geometric elements does not necessarily provide an expression with a low complexity level. Organic elements are defined as curvilinear and biomorphic, often providing a higher complexity level. Such elements are often inspired by shapes found in nature. Both geometric and organic elements consist of a variety of line qualities (in terms of thickness and expression of the line). (Pipes, 2003, pp.48-51)

The different material structures of the sun-screening textiles that are used within this thesis are defined as open or dense, or a combination of these. The open structures are areas in the textiles that have higher light-translucency values (%T), which allow more sunlight to pass through the material. A denser structure is a more compact material (with a low to zero %T), which blocks the sunlight from passing through the sun-screening textile.

3.3 The conceptual framework of established design processes, as a method to investigate novelty design processes

The conceptual framework provided for established design processes, as explained in section 3.1, was used to investigate the effects of direct sunlight on the stages of the creative development within the textile print design process when the sun is used as an activator of textiles printed with thermochromic leuco dyes. The definitions of these

stages of this creative development process, which was used as a reference for comparison, were as follows:

- Stage 1, the brief, defining the framework for the intended design process.
- Stage 2, research, involving the inspiration and sourcing of ideas for the intended design outcome, i.e. development of mood boards and image boards.
- Stage 3, design development, involving sketching and development of the imagery, by both mark making and CAD (i.e. defining compositions, colourways, and size).
- Stage 4, colour, involving creation of colour boards, and meeting requirements through colour mixing, normally carried out hands on in a print workshop or similar facility.
- Stage 5, sampling and experimenting, involving exploration and decisions on final substrate materials and printing techniques, normally hands on in the print workshop or similar facility.
- Stage 6, printing the final textiles to create the final outcome, determined by the brief, e.g., fabric samples, sample collections for presentation, textile art pieces or commercial fabrics. (Udale, 2008; Russell, 2011; Steed and Stevenson, 2012)

3.3.1 *The design brief*

A design brief for the aesthetics of the textiles (incorporating colour, fabric materials and imagery) was created by the author using self-expression and based on tacit artistic knowledge as an educated and practicing textile printmaker practitioner. (Polanyi, 1966; Niedderer and Reilly, 2010) The design brief, acting as a conceptual framework for the overall study (see section 3.1) and focused on the desired colours and material fabric qualities, was drawn up according to general practice within printed textile design as a tool to guide the design practitioner to a specific design outcome. (Russell, 2011, p.46; Steed and Stevenson, 2012, pp.70-71) The design brief was decided in advance to suit the investigations relating to the aims of this thesis were carried out. The brief was defined to include an overall inspirational visual theme from which a restricted colour palette as well as imagery were derived. Theme selection is common practice as a visual guideline and a starting point in the textile print design process, (Russell, 2011, p.47) The used of themes to provide uniqueness in a design and in so doing ‘enhance’ the visual language of the designer. (Steed and Stevenson, 2012, p.70) In addition to the overall theme, a theme keyword was selected for the aesthetics of the overall study.

The keyword was, in this research, interpreted as based on two sub-groups with a number of sub-keyphrases. The images and keywords/keyphrases selected were used as 'creative catalysts' within the print design process. The inspiration for the imagery and the colour palette was taken from both primary and secondary research. The primary research included drawings and colour studies of actual objects as well as photographs taken by the author. The secondary research included scanned imageries from literature as well as royalty-free image banks. (Steed and Stevenson, 2012, pp.36-45)

A restricted colour palette, included in the design brief, was established in keeping with the traditional emphasis on this feature of the creative process for printed textile design. Textile printmaker practitioners generally use the colour palette to convey the design concept and ideas as well as to set the mood. (Russell, 2011, p.62) They can choose to develop the colour palette alongside the imagery, although due to the particular importance of colours within printed textile designs, it is common practice to set the colour-palette already at the design brief stage. (Russell, 2011, p.62) The selection of final colours is, within this thesis, defined as a 'pre-set' colour palette to emphasise that it was created in the design brief rather than during the design of the fabric samples. This palette was set to challenge the colour design process and the limitations of the colour outcome achievable using the thermochromic dyes, including the outcomes of mixing the thermochromic dyes, in some cases in combination with permanent pigments. It was an aim to achieve similar colour outcomes from the thermochromic dyes, regardless of the supplier or the activation temperature.

The pre-set colour palette was created using printed textile design methods, aiming to contain a group of colours that would work well together. An image board of 'butterflies' was created as a colour-referencing tool. A number of possible colours that met the aesthetic colour brief were selected from the butterfly images by digitally selecting the colours using Adobe Photoshop. The selection of colours was then refined and mounted on a colour board, which defined the final hues and tints of the colour palette as well as colour proportions. The colour palette created by the colour board was then matched through screen-printed colour sampling using the thermochromic leuco dyes as well as permanent pigments until a similar colour outcome was reached. (Russell, 2011, pp.62-63)

The aesthetic design brief set also defined the aims in terms of the fabrics required to create 'enhanced' qualities when the sunlight shone through the textile material.

‘Enhanced’ material qualities refer to textiles that, both unprinted and printed with combinations from with the pre-set colour palette, would give the fabrics improved material characteristics. Examples include retaining the shine of the material, ensuring that the printed design does not dominate the structural expression of the fabrics and, where possible, enhancing the overall expression in combination with the printed surface. The section of the design brief regarding the fabrics additionally addressed the use of variety of the thickness of the substrate fabrics, so that the effects of this feature on the thermochromic colour change could be established.

Self-expression, as well as tacit knowledge, was used within the development process leading to the aesthetic outcome within the overall study. As such, these factors led the design process forward by inspiring ideas for the expressions of the final textile designs, also aiming to satisfy the vision and the design brief through the use of colours, imagery and material qualities by exploring those alternatives that provided more interesting and more attractive aesthetic expressions. The aesthetic decisions made on the basis of self-expression and tacit knowledge are referred to as ‘enhanced’ expressions or as ‘enhanced’ colour expressions.

3.4 Materials

The research used a number of different textile and related materials, such as fabrics, threads, wires, dyes etc. The use of the word ‘material’ refers to the extended selection of textile related products and not only the fabrics. A full list is given in Appendix E.

The main body of work was carried out using thermochromic leuco dyes with a colour changing activation temperatures in the range 20-47°C. Two companies supplied the thermochromic leuco dyes. Dyes with activation temperatures 25°C and 27°C were supplied by Matsui International Company Inc, Los Angeles, California, USA, (<http://www.matsui-color.com/>). Dyes with activation temperatures 20°C, 22°C, 31°C and 47°C were supplied by LCR Hallcrest Inc., Connah’s Quay, UK, (<http://www.hallcrest.com/tic.cfm>).

The research also included the following additional textile print related materials: Bricoprint standard binder SF 20E (white spirit free), Bricoprint puff-binder and Bricoprint pigments were supplied by Brenntag AG, UK. The Bricoprint pigments used were Acramin blue FFG-N, Aquarine fluorescent orange, Bricoprint red BT and Imperon yellow K-R. Thanet Coating Ltd. supplied light sensitive TC6043 Emulsion Dual Cure No.14, which was used for exposure of the silkscreen. The patterns for the

silkscreen were printed onto an Elite Essentials HD Screen Film 36'' x 30.5m (EESF-36) supplied by Colourgen.

The fabrics used were supplied by WBL Whaleys Ltd, Bradford, UK (silk-viscose satin, silk-viscose velvet, acetate satin, plain polyester-viscose weave, as well as a selection of different fabrics for the initial tests) and by Edinburgh Fabrics, Edinburgh, UK (silk chiffon, as well as a selection of fabrics for the initial tests). A variety of different white and black paper qualities, supplied by the Heriot-Watt University store as well as artist stores in Edinburgh, UK. The papers were used as conceptual supplements for textile fabrics in parts of the research.

3.5 Textile print methods

3.5.1 *Dyes and permanent pigments*

The final colours for the printed textile samples, as defined in the pre-set design brief, (see section 3.3.1) were mixed using batches of base colours. The base colours were mixed using off-the-shelf slurry colours (either thermochromic leuco dyes or permanent pigments) and a standard binder (for dye recipes for base colours, see Appendices A.1 and A.3). The base pigment colours were mixed at a ratio of 30g pigment to 1000g standard binder, regardless of hue. The base thermochromic leuco dyes were mixed at a ratio of 30g slurry thermochromic leuco dye to 100g standard binder, regardless of hue. The hues in the final colour palette were provided using different proportions of the thermochromic leuco dye and/or permanent pigment base-colour mixtures (for dye recipes for individual hues see Appendices A.2 and A.4). Throughout the research, printed fabric samples were viewed against the sun so that the hues, when prepared from mixes according the design brief, could be assessed with the sun-screening application in mind. The ratios used for mixing permanent pigments with puff-binder were 4g slurry pigments to 40g puff-binder.

The final printed samples (labelled as sample numbers 1, 2 and 3), using the 'butterfly ink' imagery, were created as a visualisation of conclusions based on results and methods of the work described within chapters 4, 5 and 6. The samples were printed with an open screen, creating even overall layers of thermochromic dyes and permanent pigments; for an example of a dye recipe, see light purple (LP) and dark purple (DP), Appendix A.4. The overall printed surface was used to ensure clarity in the imageries created by the laser-treated and devoré-printed structures. Samples 1 and 2 were printed

on silk-viscose satin and sample 3 on silk-viscose velvet. Sample 1 was printed with thermochromic leuco dyes, with an activation temperature of 31°C, supplied by LCR Hallcrest Inc. Samples 2 and 3 were printed with thermochromic leuco dyes, with an activation temperature of 27°C, supplied by Matsui Inc. Sample 1 changes colour from light purple to light blue. Samples 2 and 3 were printed with a dark purple that moves towards a dark blue when activated. Sample 1 was laser etched with motifs both before and after the printed layer, whereas sample 2 was laser-cut after the printed layer. Both samples 2 and 3 were devoré-printed (for recipes for the devoré-paste see Appendix B). Sample 3 was additionally printed with puff print to add an aesthetic structural complement to the surface structures, by creating an expression of a light relief structure.

3.5.2 *Silkscreens*

The silkscreens used for the imagery for the textile screen-printing were of a 77-T print mesh. The silkscreens were coated with TC6043 dual cure light sensitive emulsion before exposure. The imagery for the silkscreens was printed onto Elite Essentials HD screen film with black ink using an Epson Stylus Pro 9700 inkjet printer. The film was then mounted onto the emulsion-coated silkscreen with tape in a darkroom. The ‘skirt pattern’ silkscreens were exposed for 30 seconds using a RA Smart exposure and vacuum unit. The ‘graphic’ and ‘devoré’ silkscreens using the ‘butterfly’ imagery were exposed for 5 seconds, whereas the ‘ink wings’ and ‘antenna’ silkscreens were exposed for 20 seconds using a RA Smart exposure and vacuum unit. Monochromatic layers within the samples were printed using an open screen (a non-emulsion coated screen).

3.5.3 *The textile screen-printing processes*

Each textile sample was pre-treated by ironing, and cut into appropriate sizes. The textile samples were screen-printed either manually on a screen-printing table using a V-shaped, 75°-angled magnetically/electrically-operating squeegee using a 10mm diameter metal rod on a Midi MDF 31 46024 electric printing table (supplied by Johannes Zimmer, Klagenfurt, Austria). The electric screen-printing table was set at magnetic power 6 and print speed 5m/min, except when printing the silk-viscose velvet samples, which were printed at magnetic power 4 using a print speed 2m/min.

Normally, the textile samples were printed using two to four passes with the squeegee with the exception of the pile fabrics, which were printed using four to six squeegee passes. The chiffon and voiles were printed with only one pass. The textile

samples were printed on the face of the fabrics. The exception was the devoré-printed layer on the silk-viscose velvet samples, which were printed on the reverse side of the fabrics to improve the burn out of the pile structure. In order to prevent the dye and permanent pigments from bleeding into the weave structure, the chiffon and voiles were printed using a cotton backing fabric. The textile samples were dried with hairdryers between applications of the printed layers.

Curing times for the fabric samples were set at 140°C for 3 minutes, so as not to damage the sensitive thermochromic dyes which require milder conditions compared to the permanent pigments. Curing was carried out using dry heat in a controllable laboratory oven and steamer (TFO/S/IM 500mm, 8500W) supplied by Roaches Engineering.

Additional aesthetic and constructive surface effects were provided using a variety of methods and chemical treatments during the screen-printing process.

A selection of fabric substrates, constructed from both natural and synthetic fibres, was screen-printed with devoré paste to achieve the deconstructed surface expression, as defined in research question Q5, section 1.3. For the devoré-printed samples, the acid devoré paste recipe (usable for cellulose fibres, nylon, cellulose acetate and triacetate) was mixed using aluminium sulphate, solvitose MVS, water and a wetting agent (for dye recipe see Appendix B). The devoré paste printed layers were dried using hairdryers before the textile samples were heated. The sample was ironed on the maximum setting to achieve the burnt out fibre effect. A light brown colour of the devoré-printed layer of the sample was needed, to obtain the required level of deconstruction. The burnt off fibres (the pile in the velvet samples) were then peeled off by hand using the protection provided by a facial mask, gloves and a fume cupboard. After this, the samples were subjected to a warm wash and then rinsed in a cold wash. The samples were measured before and after wash to establish the percentage that the samples had shrunk.

Parts of some fabric samples were also screen-printed with colours mixed with puff-binder rather than normal pigment binder in order to provide a rubbery ‘relief’ structure after heating. The printed textile samples were ironed on maximum setting until the required embossed effect was achieved. During heating, an intermediate layer of cotton fabric was used to cover and protect the puff-printed structure.

All printed fabric samples were numbered and catalogued. The samples printed with permanent pigments were labelled ‘pigment-TX’, where T refers to test and X is the sample number. The samples printed with thermochromic leuco dyes, some printed together with permanent pigments, were labelled ‘Th.ch-TX’. Samples printed with added print related effects were labelled according to the method used; ‘Devoré-TX’ for devoré-printed samples and ‘Puff-TX’ for puff-printed samples.

3.6 Laser technology methods

The laser-treatment experiments required to achieve a deconstructed surface expression, as defined in research question Q5, section 1.3, were conducted using a FB Series laser-cutter supplied by GS UK Ltd. UK. These experiments were conducted using both unprinted white substrate samples and a variety of screen-printed fabric samples.

The computer software used during the investigations were Adobe Illustrator (AI-files), Adobe Photoshop (JPEG-files) and ApS-Ethos (ISI-files). Preparations of the imagery were carried out using the first two programmes and the last was used when operating the FB Series laser cutter machine. Both pixel-based Adobe Photoshop and vector-based anchor point Adobe Illustrator designs were used in the research. JPEG and AI-files were used for the etched imagery samples and AI-files for the laser-cut samples. The imagery consisted of either open or closed shapes or lines. All files were, after being imported into ApS-Ethos, converted into ISI-files. Minor variations to the designs were carried out using Ethos, such as re-scaling, rotating or minor alterations to anchor points. The ApS-Ethos software was found to be more restrictive when creating the designs. It was therefore preferable to complete the imagery in either Adobe Photoshop or Adobe Illustrator.

The fabrics were pre-treated by being ironed and mounted on to the iron bed of the laser machine. A solid silver bed was used for the etched samples and likewise a black honeycomb bed was used for the laser cut samples. The fabric samples were both laser-etched and laser-cut using the standard laser beam height of 12mm and a lower setting of 5mm between the fabric and the laser-head of the machine (see Figure 3.7).

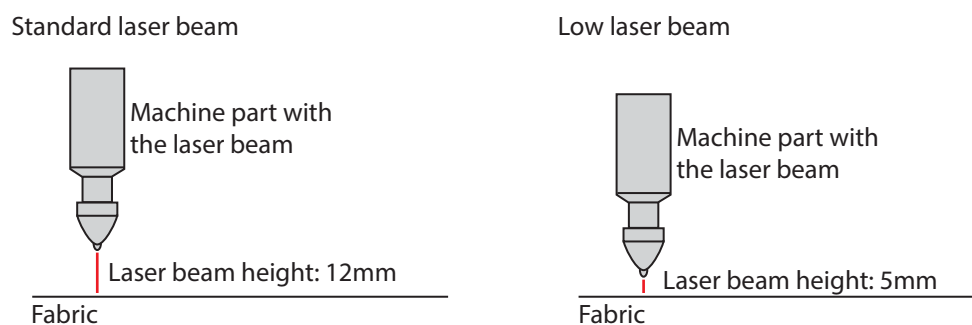


Figure 3.7 Illustrations of the normal and the lowered laser beam setting of the laser cutter.

Depending on the fabric and laser technique used, accurate computer settings (beam height, velocity percentage, maximum and minimum power, and scale line width) were set prior to the information being imported into the laser cutter. Textile materials behave differently depending on fabric structure and fibre quality when laser-treated. This means that every textile substrate required to be optimised separately. An experimental investigation was undertaken with the purpose of finding an interesting aesthetic expression as well as a functional light-transmitting surface, as defined in research question Q5, section 1.3. All investigations started with the default setting recommended by the supplier of the laser-cutter, (see Table 3.1).

Table 3.1 The different default settings for materials for the FB Series laser-cutter

Material	Laser technique	Default settings recommended by the supplier				
		Velocity	Min power	Max power	Scan line	Beam height
Silk-viscose pile*	Laser etching	60.0 cm/s	5%	30%	0.3	Normal
Silk-twill**	Laser etching	60.0 cm/s	5%	15%	0.2	Normal
Silk-viscose pile*	Laser cutting	10.0 cm/s	5%	60%	- (not used)	Normal
Silk-twill**	Laser cutting	8.0 cm/s	5%	30%	- (not used)	Normal

* The silk-viscose pile setting was used for silk-viscose velvet.

** The silk-twill setting was used for silk-viscose, acetate, cotton velvet and the screen print mesh, due to similar weight and thickness to the silk-twill.

Thereafter, the instrument setting was changed step-by-step, until an aesthetically enhanced as well as a light transmitting result was found. If an unappealing result was obtained, this was evaluated and then the instrument settings were altered accordingly. The laser-treated sample using the new instrument setting was then evaluated. The process was repeated until a satisfying result was obtained or until the combination of fabric and imagery was discarded. All samples were numbered and catalogued with the

T and X notation as defined in section 3.5.3. ‘Etch-TX’ was used when the textile sample was laser-etched, ‘Cut-TX’ when the sample was laser-cut, and ‘Etch&Cut-TX’ when the sample was both laser-etched and laser-cut.

3.7 Observation methods

The methods described in this section were used to study the thermochromic colour change when using the sun to activate thermochromic leuco dyes applied to textiles. These methods were based on observations of both the textile samples and the light conditions. The observations were carried out in both natural and artificial sunlight. The observations were carried out at the following geographic locations; the Scottish Borders, UK, (latitude 55.55°N-55.62°N; longitude 2.89°W-2.84°W), Copenhagen, Denmark, (latitude 55.68°N; longitude 12.57°E), and the Scania region (Skåne), Sweden (latitude 55.70°N-55.93°N; longitude 13.19 °E-13.55°E).

3.7.1 *Daylight conditions*

The definition and interpretation of the level of sun and different sky conditions used in the observations were based on *Lighting Design and Simulation Knowledge base’s ‘Lighting Design Glossary’*, quoted as follows.

‘Lighting Design Glossary

For day lighting purposes, the CIE declares a number of sky conditions as standard skies. Those are defined by functions, depending on the solar altitude, even when the sun is hidden.

Sunny sky *is any sky condition where the sun happens to shine (through the clouds, if there are any). This can be combined with any of the following three conditions.*

Clear sky *has less than 30 % cloud cover, or none. This sky is most likely to be combined with sun.*

Partly cloudy sky *has between 30 % and 70 % cloud cover. This sky can be combined with sun in some cases.*

Cloudy sky *has more than 70 % cloud cover. This sky normally excludes the sun.*

Overcast sky has a completely closed cloud cover (100 %). Obviously, this sky can't be combined with sun in a meaningful way. This is the sky condition applied in daylight factor calculations.

(Lighting Design and Simulation Knowledgebase, n.d.)

These definitions were amended further to suit the purpose of the investigation, for example to reduce the number of variables and the complexity of the analysis. The sky conditions were redefined into the two sky conditions judged to be appropriate in the context of this thesis; 'sunny sky' and 'cloudy sky'. The first redefined sky condition was a sunny sky combined with 0-15% clouds, based on the original definitions of the sunny and the clear sky conditions in 'Lighting Design and Simulation Knowledgebase'. 'Cloudy sky', the second redefined sky condition was defined as a sunny sky combined with 25%-80% clouds, based on the original definitions of partly cloudy and cloudy sky conditions in 'Lighting Design and Simulation Knowledgebase'. Sky condition 'overcast sky' was disregarded in this investigation, since this provided no sunlight for the required activation of the printed thermochromic dyes.

The two settings, sunny and cloudy sky, were additionally defined in relation to illuminance. Illuminance is measured in the metric unit lux. 1 lux corresponds to the amount of light that falls over 1m² of surface (1 lumen). (Bougdah and Sharples, 2010, p.141) The definitions of the lux values within this thesis, 90,000-110,000 lux for sunny sky conditions and 20,000-35,000 lux for cloudy sky conditions, were based on both literature references as well as measurements of the illuminance carried out by the author during the two redefined sky conditions. Measurements of illuminance were conducted with a LX1010BS luxmeter supplied by Dr. Meter. The light sensor of the luxmeter was angled towards the sunlight during the measurements. The general external illuminance for sunny sky is reported as around 100,000 lux, but can on a bright sunny day exceed 100,000 lux. (Halsted, 1993) Measurements conducted in a sky conditions with 0%-15% clouds, redefined as sunny sky, carried out within this thesis during June to August resulted in readings in the range 90,000-110,000 lux. Lux values of external illuminance during cloudy sky can vary depending on the density of clouds. A cloudy sky is reported generally to provide values around 10,000-25,000 lux (not in direct sun) but also readings up to 35,000 lux. (Halsted, 1993; Schlyter, 1997) Measurements conducted during a sky condition with 25%-80% clouds, redefined as

cloudy sky, carried out within this thesis during the months of June to August gave readings in the range 20,000-45,000 lux.

3.7.2 *Sunlight observations: indoor and outdoor*

The observations of the printed textile samples were conducted using the sun as the light source. These results were assessed in terms of the impact the sunlight had on the aesthetic appearance of the printed textiles. During observations, textile samples were integrated into two different set-ups (indoors, A and outdoors, B). Textile samples were ‘back-illuminated’; in this case the fabrics were placed between the observer and the light source, so that light passed through the textile sample (see Figure 3.8) before reaching the observer. Textile samples were viewed from three different observation distances (0.2, 5 and 8m) and at a variety of different viewing angles (see Figure 3.9-3.10). The ambient temperature of the indoor set-up mostly varied in the range 20-22°C. The ambient temperatures of the outdoor set-up were much more varied, due to the seasonal differences (see Appendix D).

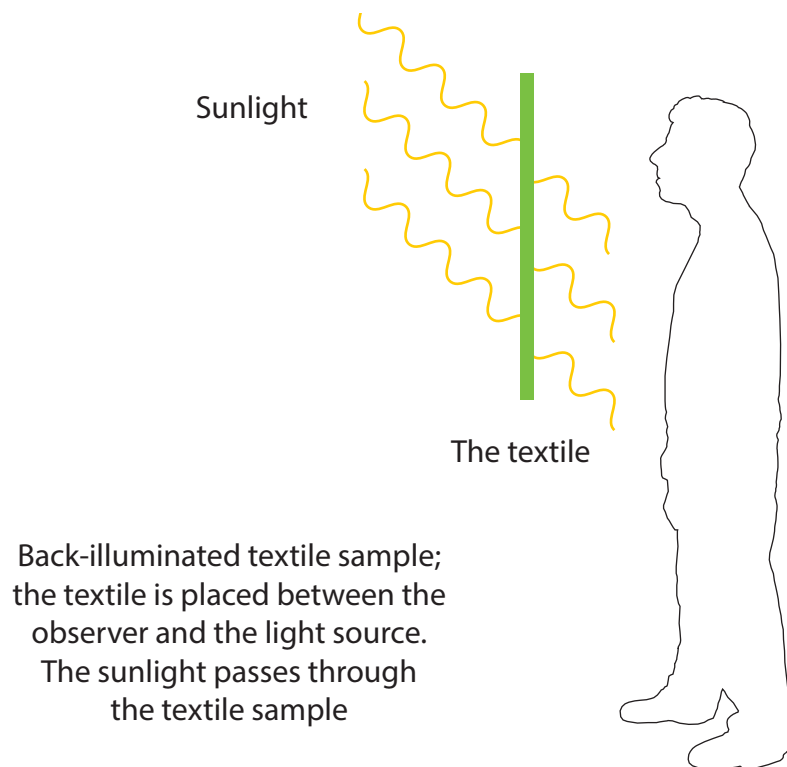


Figure 3.8 Illustration of the back-illuminated textile sample.

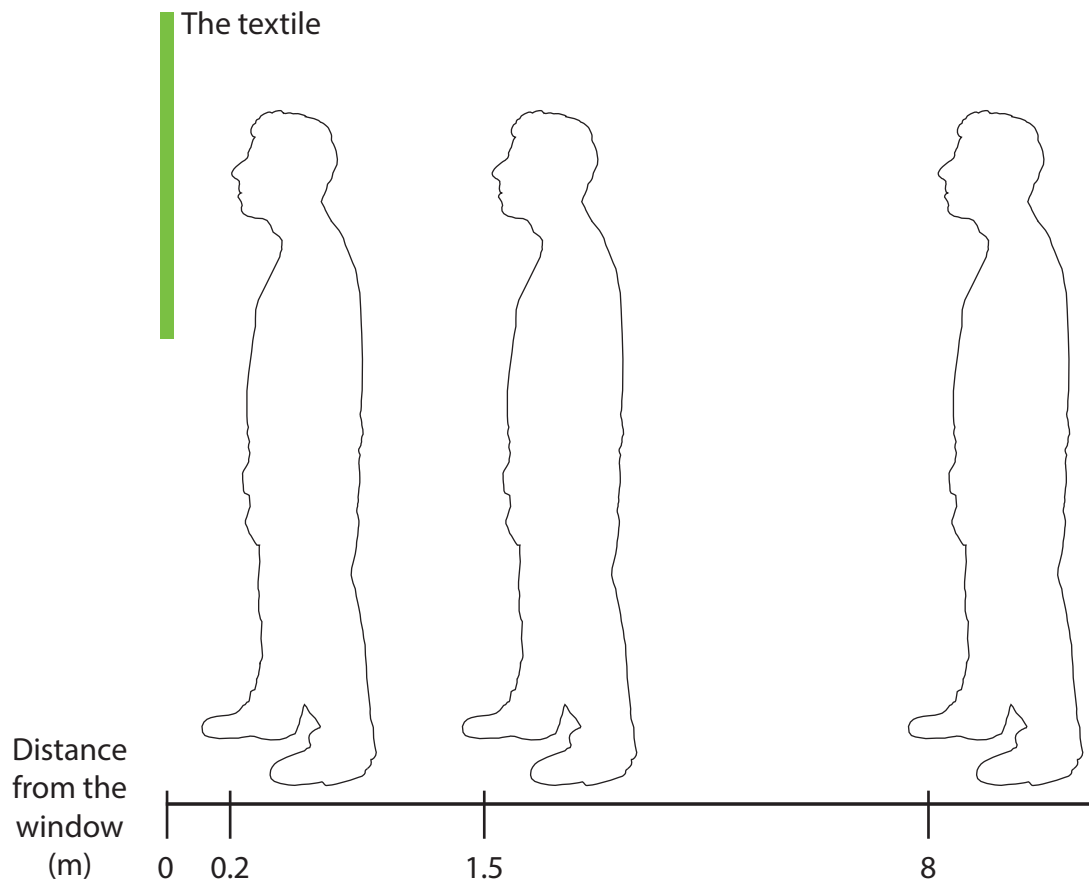


Figure 3:9 The three viewing distances, 0.2m, 1.5m and 8m.

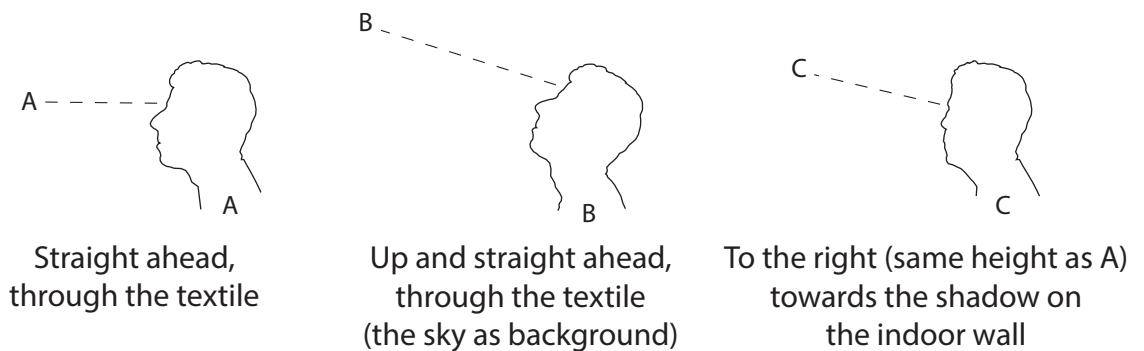


Figure 3:10 Viewing angles A-C (head positions and lines of sight) that were used during the sunlight observation of the fabric samples and light conditions.

The researcher's field notes, created immediately to document the observations, were recorded in notebooks and/or on the computer. (Mehan, 1992; Fretz, Shaw and Emerson, 1995) Field notes included both descriptive accounts of the set-up used and the time and date of the events, as well as the researcher's reflections on particular observations. Several of the textile samples were also photographed and some filmed to clarify the outcome of the observation. An assessment of sky conditions as well as viewing distances were logged in

the field notes. Each textile sample was viewed on a number of separate occasions to provide an understanding of the impact of different sky conditions on the possibility to achieve activation of the thermochromic dyes (colour change).

The observation of the screen-printed textiles, indoors as well as outdoors, was aimed at understanding the influence of the differences in ambient temperature in relation to the chosen activation temperatures of the thermochromic dyes. For the indoor observation set-up A, the textile samples were mounted on a westerly facing windowpane on the first floor of a building (see Figure 3.11). The samples were viewed from two viewing angles (A and B) as well as from the three viewing distances.

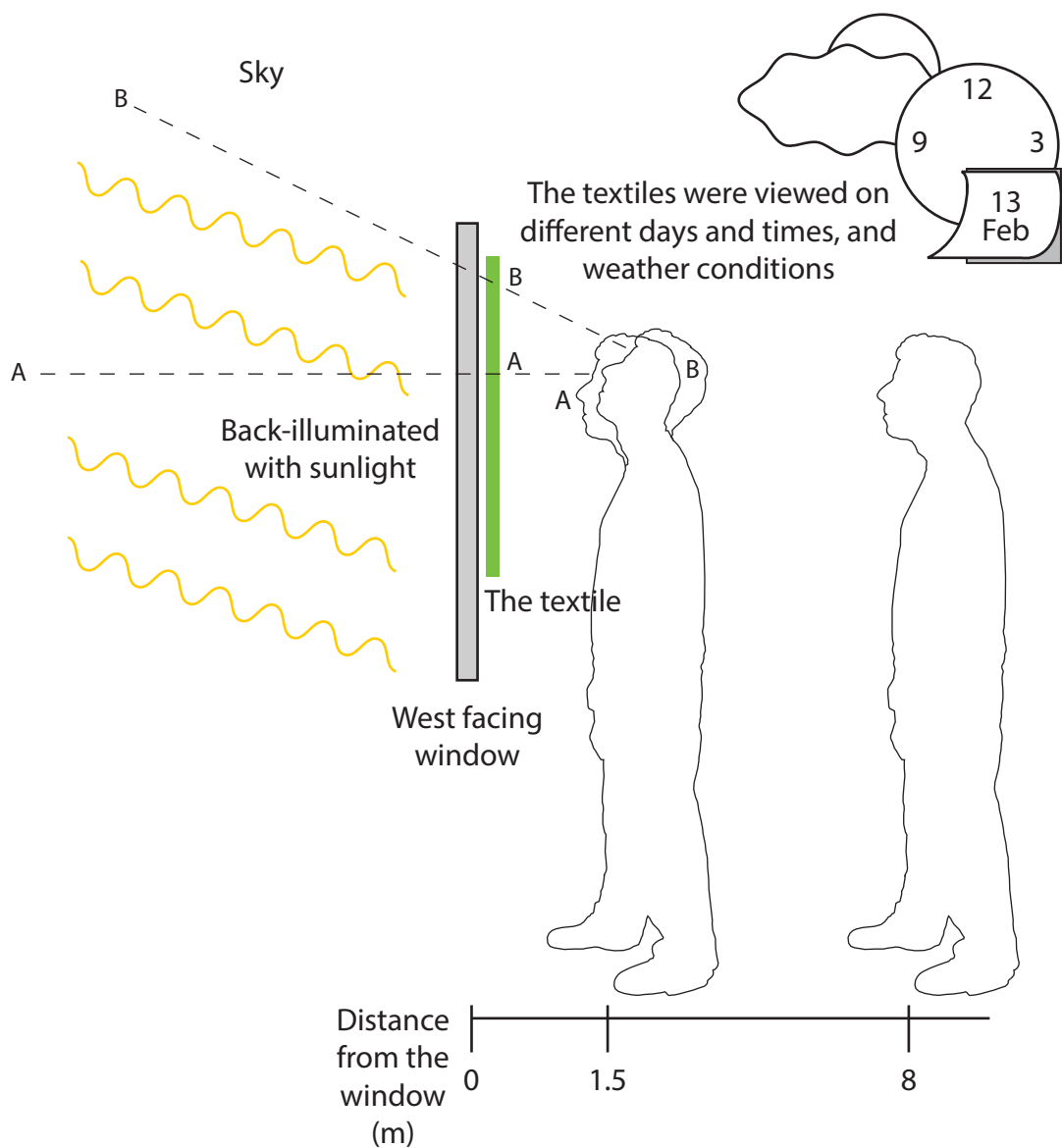


Figure 3.11 Set-up A, indoors, when observing the textile samples on a windowpane.

The same set-up and viewing variables were used outdoors (set-up B) as indoors, in order to provide a comparison. The difference was that the textile samples were mounted on a tripod outdoors and on a windowpane indoors (see Figure 3.12).

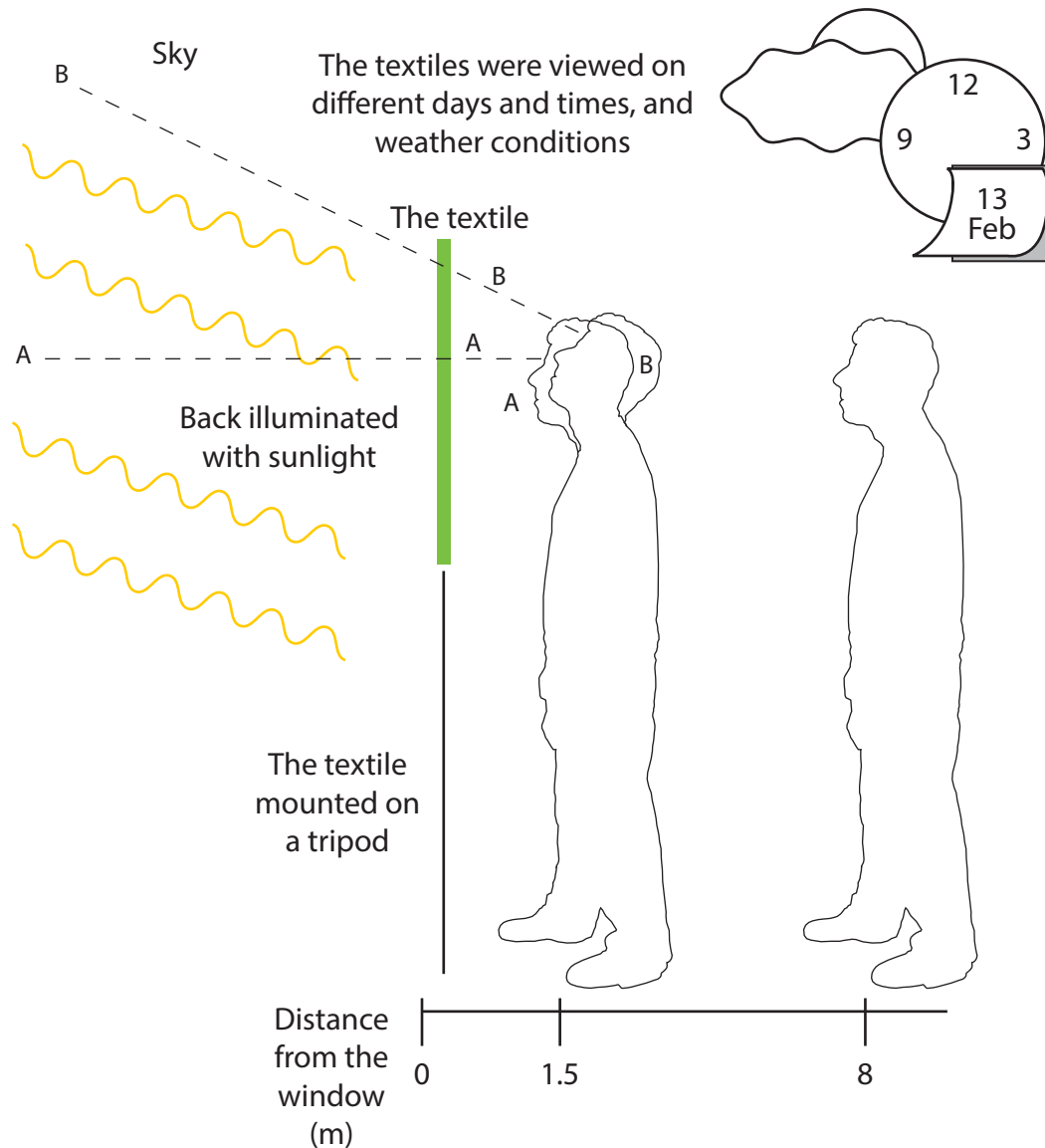


Figure 3.12 Set-up B for observing the textiles outdoors on a tripod.

The sunlight observations of textile samples treated using laser technology and/or printed with devoré paste were carried out solely in the indoor set-up. In this case, observational methods focused on the effects of the illuminated imagery (referred to in this thesis as light imagery) that appeared within the translucent areas of the samples as well as the light and shadow patterns created on the walls and ground when the sunlight passed through the laser-etched surfaces. These methods were used in order to lead towards an answer to research questions Q5 and Q6 section 1.3. A study of the illuminating imagery was made to evaluate and establish changes involving the focal point (for definition see

3.2.5) of the sun-screening textile. Observations of the light and shadow imageries were carried out to understand the relationship between the light translucent imagery of the sun-screening textile and the light and shadow imagery projected on the surrounding surfaces (i.e. walls and the ground). A flat white surface, acting as a projection screen, was placed to the right of the observer, in order to ensure clarity in evaluating the movements and changes of the light and shadow imagery (see Figure 3.13).

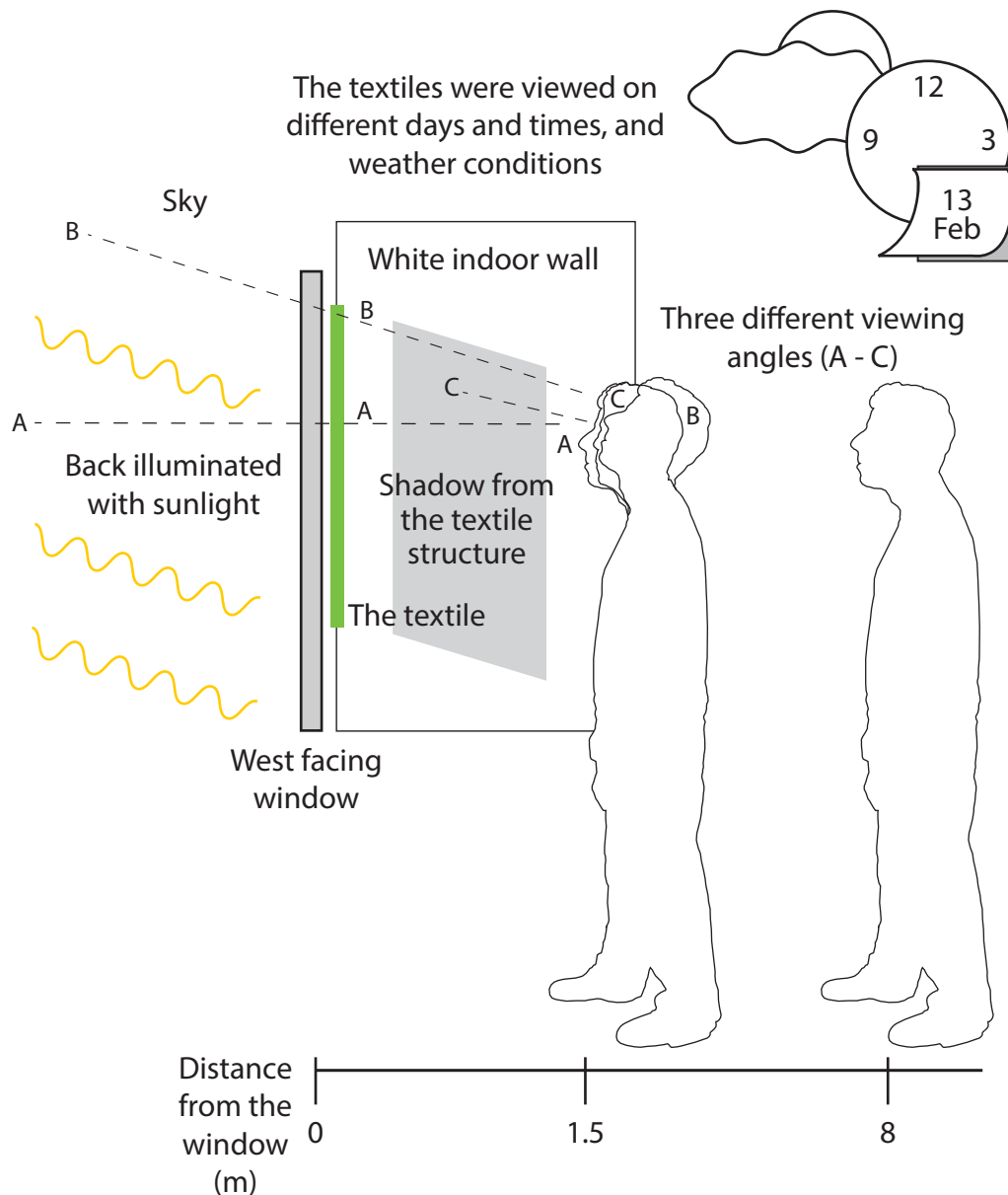


Figure 3.13 Set-up C, indoors, for observing samples that have been laser-treated and/or printed with devoré paste.

3.7.3

The Natural Colour System visual colour identification method

A Natural Colour System (NCS) atlas was used using set-up (A2), as illustrated in Figure 3.14, to quantify the observations of the colour outcome when printing the pre-set colour palette (for a discussion of the pre-set colour palette, see section 3.3.1) using dyes from different suppliers and with different activation temperatures.

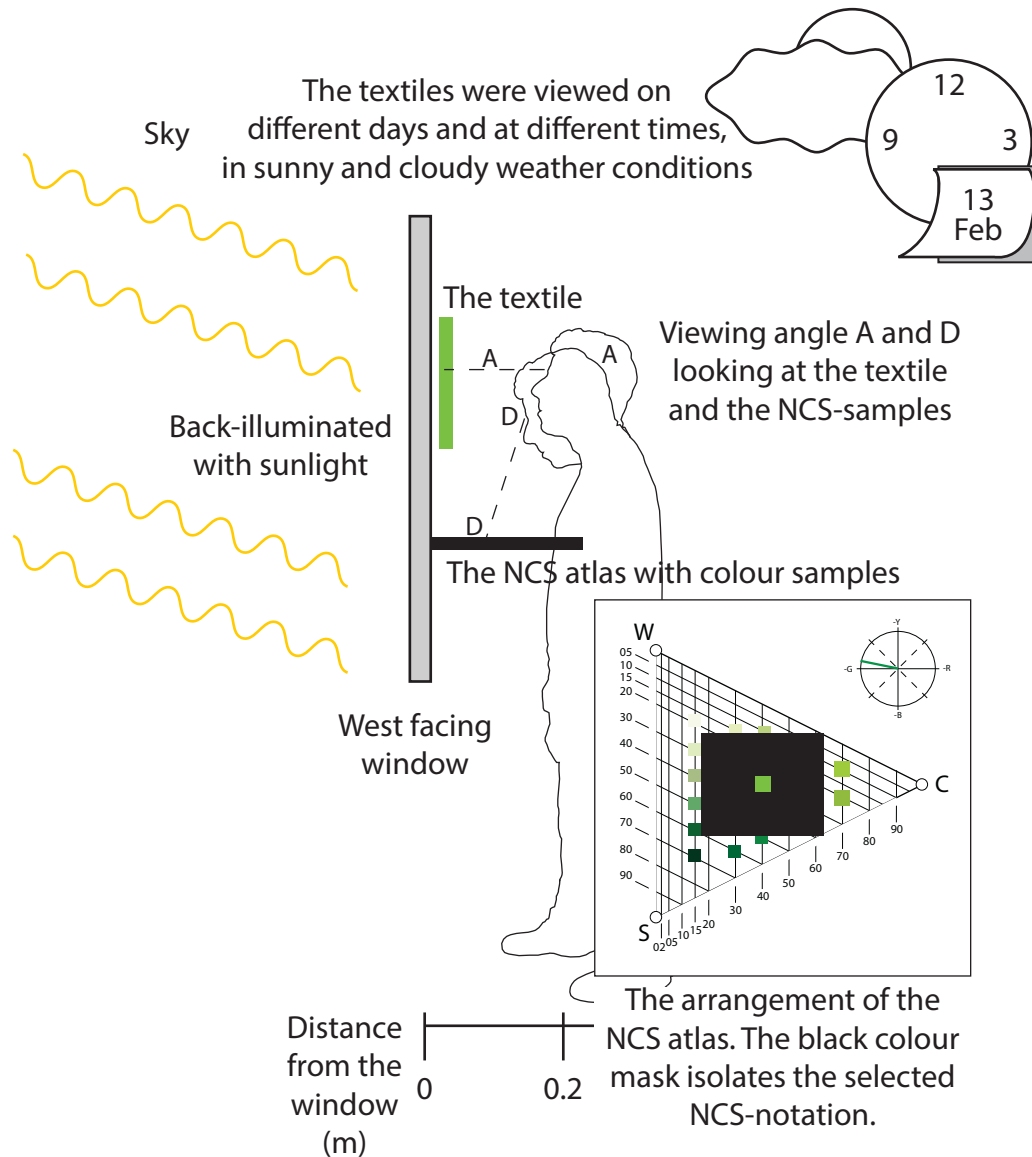


Figure 3.14 The NCS visual colour identification method of set-up A2, indoors. Printed fabric samples are placed on the windowpane.

The colour outcome of the printed textile samples was compared to the colour of the samples in the NCS colour atlas that are defined by the NCS colour notations, which are the numeric colour codes in the NCS Colour Space. On the basis of visual comparison, the NCS colour notation of the sample in the NCS atlas that was perceived

as closest to the colour of the printed textile samples was then documented. The NCS mapping method (for set-up A2) was applied based on the sunlight observation (set-up A) (see Figure 3.11). The printed textile samples were mounted on the windowpane as in indoor set-up A. Viewing angle A, as defined in Figure 3.10, was used as before, and additionally viewing angle D was used (see Figure 3.15). As explained in section 3.2.4, the results of these NCS colour notations were visualised by plotting in the NCS colour circle and the NCS colour triangle (see Figures 3.2-3.4).

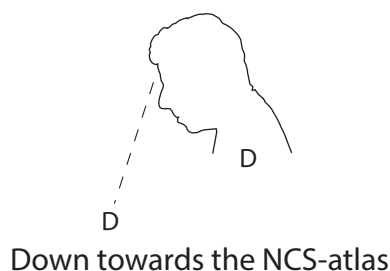


Figure 3.15 Viewing angle D, (head positions and lines of sight).

This colour identification method, based on the visual evaluation of the colour appearance of the textile samples is considered to correlate well with the process of a designer, who generally works with visual values, interacting with all stages of the design process, such as visual research, visually matching the colour ways through to visual presentation. (Steed and Stevenson, 2012) A final result of a textile design is probably more often evaluated aesthetically through visual colour assessment rather than by scientific measurement.

3.7.4 *Light observations within a scale model*

Light observations, using a variety of artificial light sources, were carried out using sun-screening material samples mounted on a scale model of a street. The purpose of placing the sun-screening material within the model, as carried out in the distinct study in chapter 5, as defined in section 3.1, was to provide an understanding of size proportions involving people in a space and changes in the colour and the perception of imagery. Firstly, the methods were used to study the projections onto the surrounding surfaces within the model of the light and shadow imagery created through light translucent areas of the sun-screening textiles. Secondly, the methods were used to establish the behaviour, in terms of the light and shadow imageries, as the thermochromic dyes changed to colourless in their active state (state 2). The scale model was used to simulate outdoor applications.

Two situations for observations were used in the investigations involving the scale model. The first situation, set-up D, illustrated in Figure 3.16, used a LP-LED 3W/power LED 12-24V lamp as the light source. The LED lamp in observation scenario D was kept in a fixed position above the material samples during the experiments. This simulated the position of the sun at noon on the 21st of June in the Northern hemisphere.

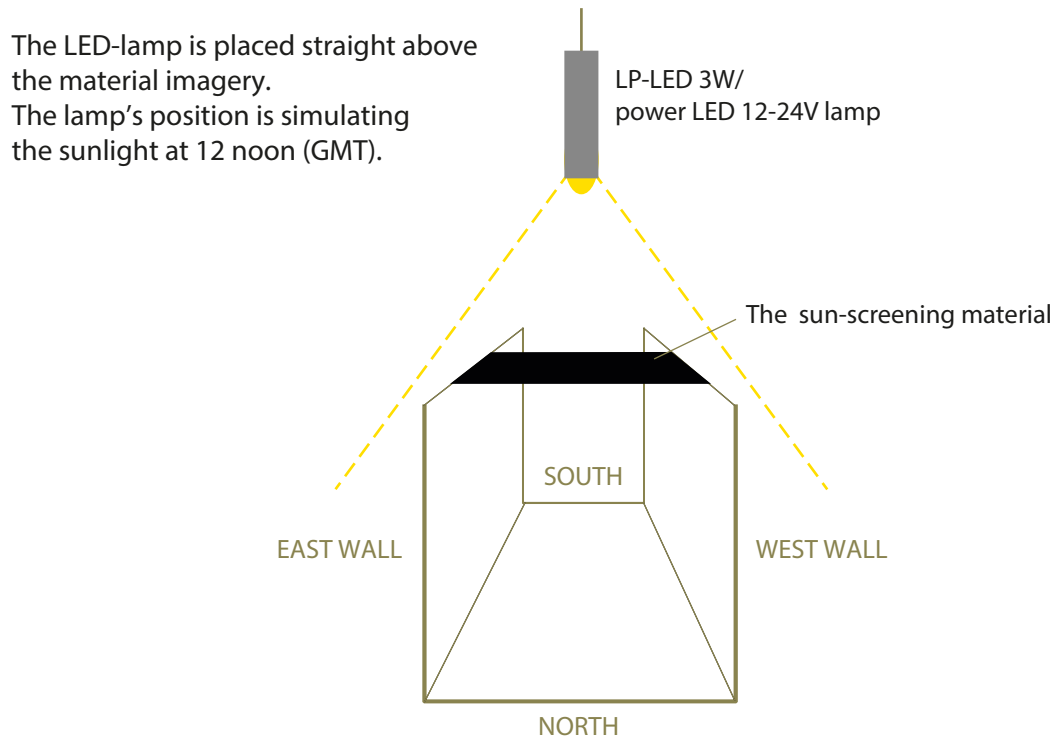


Figure 3.16 Observation set-up D with an LED-lamp.

The second situation, observation set-up E, illustrated in Figure 3.17 in the scale model uses a 100W, 2V, HLX 64625, GY 6,35, XENOPHOT halogen display/optic lamp, supplied from Osram. The illuminator is fitted on a 63 cm diameter parabolic reflector. The lamp and reflector are mounted on a movable arc in a daylight laboratory. A daylight laboratory is a room with technical equipment that can simulate the sunlight, the path of the sun, colour temperature and sky conditions, at any geographical position on earth. The daylight laboratory is normally used in investigations of the relationship between architectural models of planned buildings and sunlight within a built environment. The daylight laboratory used within set-up E in this research is located at the Royal Danish Academy of Fine Arts, School of Architecture in Copenhagen, Denmark. This essentially provided an artificial sun, which was combined with an artificial daylight sky.

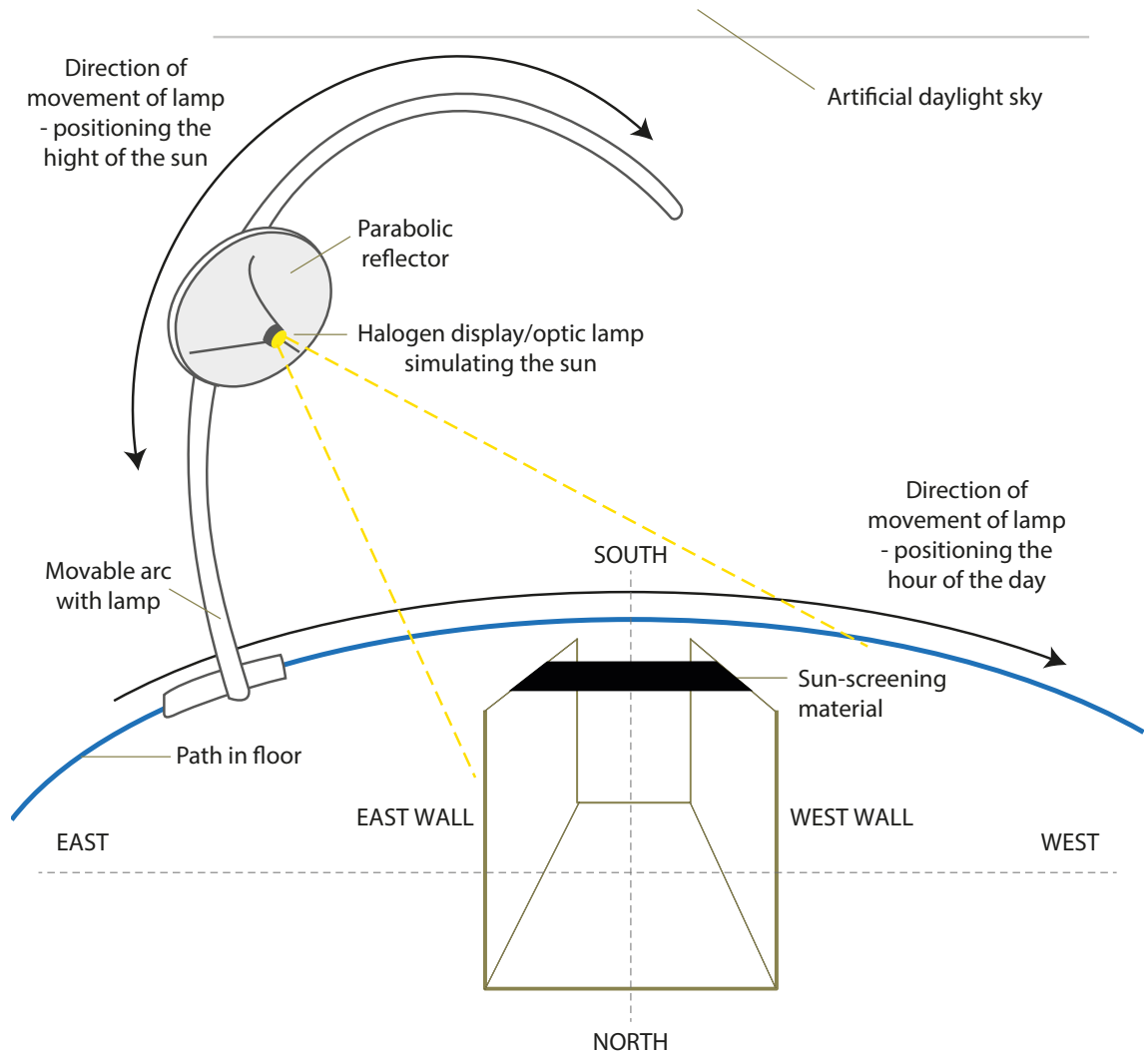


Figure 3.17 Observation set-up E in the daylight laboratory.

The artificial daylight sky used covers a room with a ceiling area of 20m^2 under which there are a large number of fluorescent tubes in three different white colours with good colour rendering properties (the illuminators provides 0-9000 lux horizontally). Below these light sources there is a translucent fabric, whose role is to diffuse the light. The sky simulates daylight conditions that correspond with a CIE standard overcast sky. The daylight sky variables on the control panel in the daylight laboratory were set at a constant maximum during the experiments, to represent sunny sky. All four walls of the daylight room are completely covered with glass (iron-free), which creates an eye level viewing angle effect.

The focus of the investigation in chapter 5 using set-up E was on the relationship of the light and shadow imagery displayed on the ground and walls with the path of the sun through the sky. The artificial sun was mounted on a metallic arc, which could be

moved by hand. When manually displaced along the track in the floor in the laboratory, the lamp simulated the sun's path accurately. A sun diagram was created so that time for the sunrise and sunset could be recorded (see Figure 3.18). The time lines (the seven dark blue lines) in the sun diagram represent the twelve months of the year. The top time line represents December and the lowest one represents June. The remaining five time lines represent each two months, one in each half of the year (January/November, February/October, March/September, April/August and May/July). The paths of the sun investigated in the daylight laboratory were set to the daylight hours between the 20th and the 22nd for each month. The investigation covered all twelve months to provide an understanding of the effects derived from the yearly path of the sun. The research also included an in depth investigation into the longest day of the year (the summer solstice), the 21st of June, to provide further information as to the movement of the sun during a 24 hour period.

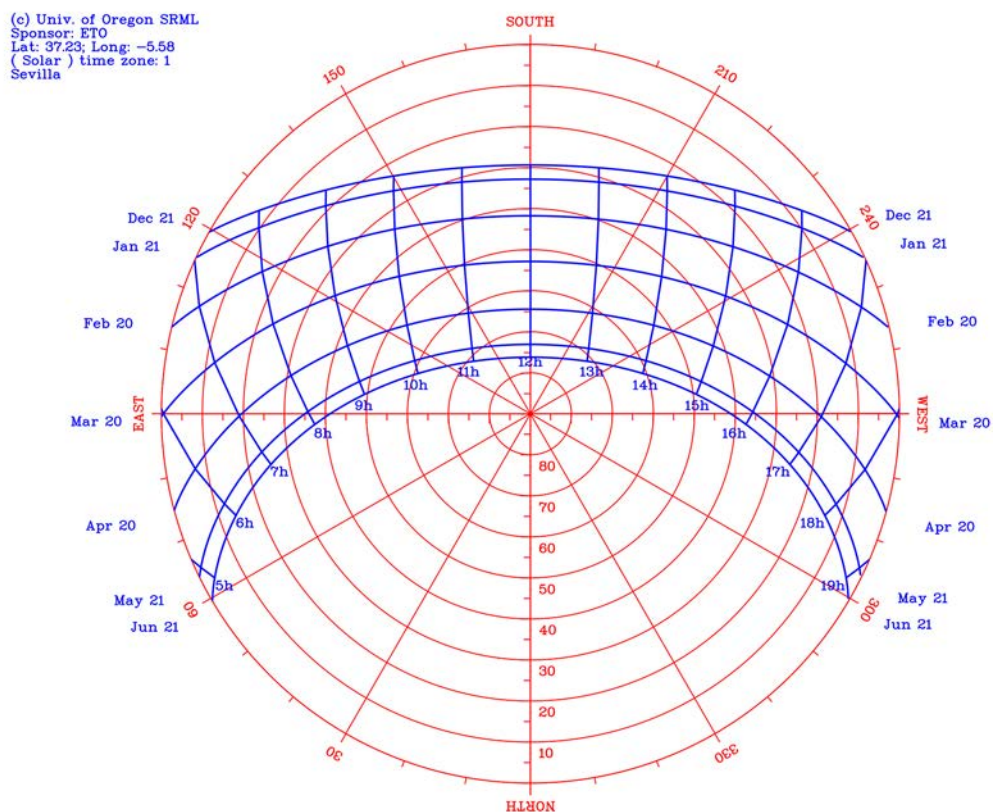


Figure 3.18 Sun diagram using the example of Seville, Spain (latitude 37.23°N; longitude 5.58°E).

The white foam-board model in set-ups D (Figure 3.16) and E (Figure 3.17) was constructed to a 1:20 scale. The model included scaled people (with an average actual height of 1.70m), to create relationships of the sun-screening materials and the

displayed imagery with the three-dimensional space as well as the human body. All details of the street represented were stripped away so that there was a focus on the material samples acting in a sun-screening role, as well as the walls and ground on to which the light and shadow imagery was projected.

3.8 Methods using artificial sources of heat and light

Light and heating experiments using artificial light sources were carried out in a professional photographic studio in Sweden. For these experiments, the equipment used included daylight lamps, spotlights, fans and light reflectors. Set-up F (see Figure 3.19) was used as a method to investigate the possibility of using artificial light, light reflectors, dimmers and fans in different combinations to heat the thermochromic dyes, rather than using natural sunlight. The photographic studio was used because all interfering natural daylight could be excluded. This meant that the investigation of the printed sun-screening textiles was focused only on the perceived effects created by artificial light and heaters.

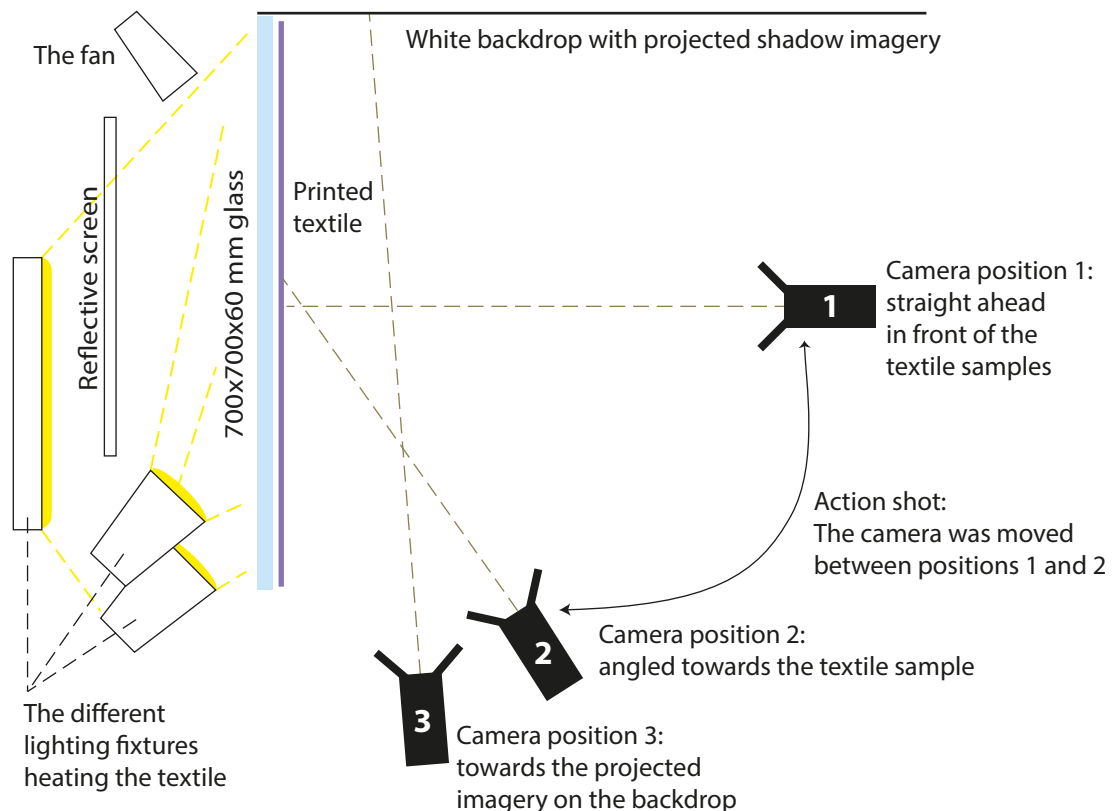


Figure 3.19 Set-up F with video cameras and a glass pane.

The aim of set-up F was to establish whether, for pedagogical purposes, the artificial light and heat set-up could visually produce similar effects (colour outcome as well as light and shadow changing behaviour), as had previously been observed in the

natural sunlight scenarios (as explained in section 3.7.2). Thus, set-up F could be used as an informative tool, by the designer, to communicate the analysed information gathered through the observation using natural sunlight (set-up A, A2 and B) to an appropriate audience. The conclusions from the previous practical observations were used to provide guidelines for the experiments using artificial light and heat. The investigations using set-up F resulted in the concluding visualizing results illustrated in Films 1-5, on the CD-ROM.

Scandinavian Photo in Sweden supplied the lighting fixtures as described below: bulbs and tripods, which were used in the investigation conducted in the photographic studio; three (two behind and one in front of the textile) 800W 'warm light' Ianiro Redhead lighting fixtures fitted with an Osram R7s 240V/800w 64571 P2/13 DXX bulb with a 3200K value, and two (one behind and one in front of the textile) Falcon Eyes lighting fixtures each fitted with 4x55W FL-554V daylight fluorescent lamps with a 5000K value. The lamp behind the textile operated as a heat source for the thermochromic dye, whereas the one in front of the textile acted rather as an illuminator during the film shots. All lighting fixtures were fitted on Manfrotto 1004BAC tripods. Furthermore, one 75 cm Lastolit reflective screen and one white 150x150 cm Euroroscreen Connect Floor Tripod 1:1 screen, as well as Show tec, BO-6-PW, 5 pins, 380V, dimmers were used.

In set-up F, the textile samples printed with thermochromic dyes (see final samples 1, 2 and 3 in section 3.5.1) were mounted in front of a mock-up window, made using a 700x700x60 mm sheet of glass. The glass was framed using white foam board. The window was placed next to a white indoor wall created using a plain white backdrop to ensure contrast and clarity of the projected shadow and light imagery.

The investigations were documented using both film and still photography. The first camera position was at right angles to the window, head on to the textile samples. The cameras were then positioned at two different angles in order to document the textile samples from the side as well as the shadow imagery on the backdrop due to the textile as illustrated in Figure 3.19.

3.9 Methods used in the collaborative study

A collaborative project was conducted jointly by the researcher and textile designer B. Jansen from the Swedish School of Textiles, Borås University, Sweden. The distinct

study described in chapter 5, as defined in section 3.1, that was carried out within the collaborative project aimed to investigate how the sun might be utilized to enhance the aesthetic expression by the incorporation of textile surfaces in urban environments. The purpose, set by the aims of this thesis, was to transfer information gained during this collaboration to the investigations relating to the devoré-printed and laser-treated textile samples in addressing research questions Q5 and Q6, section 1.3. The crossover with the research leading to Jansen's thesis added interesting synergies of input and ideas between the two projects.

The collaborative project explored the possibilities offered by textiles as a means of aesthetic interplay and as a sun-screening element within an outdoor public architectural space. A scenario, a street in Seville, Spain (latitude 37.23°N; longitude 5.58°E) was constructed to form a framework for the investigation from which the analysis could be conducted and evaluated. The investigation examined the change within visual aesthetic expressions of changeable light and shadow imageries provided by the imagery of the sun-screening textiles. The light and shadow imagery, which was projected on the walls and the ground of the street, was studied at noon through set-up D (see section 3.7.4 and Figure 3.16) as well as during the hours of sunlight through set-up E (see section 3.7.4 and Figure 3.17). The research was carried out using the 1:20 scale model, as defined in section 3.7.4. The model, built to a 1:20 scale, was constructed so that an estimate could be made by extrapolation of the impact of the imagery within a full-scale textile design situation. Scaled people were included in the scenario, which provided the ability to investigate the relationships between the sun-screening materials, the displayed imagery within the three-dimensional space and the human body. The street was placed along a line of longitude so that the rising of the sun would hit the east wall at a 90° angle, and the setting sun would hit the west wall at a 90°.

A mood board was created to define the atmosphere of the environment of the selected street scenario. Aesthetic choices within the investigation as well as the creative development process were informed by the two researchers' self-expression. (Niedderer and Reilly, 2010) Analyses of the investigations were conducted during the experimental investigations of the projected imagery. The same investigations were analysed from documentation using video and photographs. The video camera was placed at the north end of the street so that the whole street was in view. The camera was moved between three different positions during the documentation of the movements due to the sun's path

(see Figure 3.20). The first camera position was aimed at the east wall. The second position was aimed at the ground, when the sun was overhead. The third position of the video camera was aimed at the west wall. In order to focus on the light and shadow imagery on the ground and walls, colours were not studied in the initial phase of the collaborative project. Colour was brought into the second phase of the project in order to simulate the areas within the sun-screening textiles printed with thermochromic leuco dye. Sound recordings of discussions during the investigation were made by the video camera. Parts of these discussions were later transcribed and used for further in depth analysis, as described in section 3.1. The conceptual idea of the thermochromic colour change was illustrated using stop-motion animation.

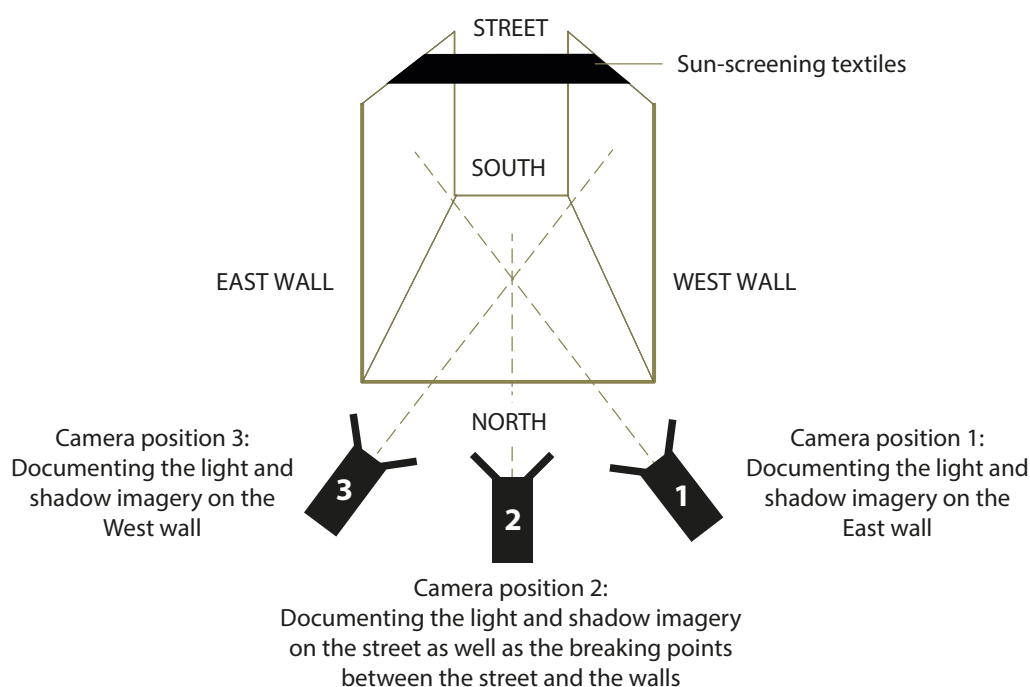


Figure 3.20 Set-up G of the video camera and conceptual street scenario.

3.10 Light transmittance method

Light transmittance tests were carried out using a UV/VIS spectrophotometer, Lambda 2, supplied by Perkin Elmer. Firstly, the spectrophotometer was used as a quantitative analysis method to compare the transmittance properties of the different devoré-printed and laser-treated structures. Secondly, the spectrophotometer was used to measure the behaviour as the colourless active phase of the thermochromic dyes (state 2) is formed. The spectrophotometer measured the amount of light transmitted through the fabric in relation to amount of incident light. The light beam passes through the fabric and the instrument registers the amount of light reaching the sensors on the other side of the fabric sample. A

small part of the fabric to be tested was placed in the spectrophotometer. The light transmittance values (%T) were measured using the full spectral range (300-700nm) of the spectrophotometer. A light transmittance value of 100%T represents a fully transparent surface (e.g., cut out completely) where all light passes through. A 0%T value represented a fully opaque surface where no light passed through. A hairdryer was used to activate the thermochromic dyes, during light transmittance tests of the active state of the printed dye. The values of light transmittance of the samples that were laser-treated and devoré-printed were systematically compared with the equivalent untreated fabric samples (defined as a 'non-treated fabric'). The value given by the non-treated fabrics was used as a reference value for the treated samples. The numerical results from the spectrophotometer tests were plotted as a graph of the light transmittance (%) against wavelength (nm).

3.11 Methods for investigating the capacity of solar cells to power the heating mechanism for the printed thermochromic leuco dyes

The possibility to utilize the sun as an indirect heater of textile samples printed with thermochromic leuco dyes, by using the sun to power a heat circuit using solar technology, was investigated using the following methods. The solar cell and heat circuit experiments were conducted using both a specifically constructed light box with halogen lamps for activation of solar cells, which were of the type recommended for this purpose by Professor John Wilson, School of Engineering and Physical Sciences, Photonics and Quantum Sciences at Heriot-Watt University, UK, as well as using natural sunlight to activate the solar cell. A power pack, 0-10A and 0-3V adjustable DC Skytronic 650.682, was used to initially investigate the efficiency of the heat circuits. In relation to the status of current technical research into solar energy conversion, the method of future scenarios was used to discuss the possibilities of more seamless solutions to the activation of thermochromic fabrics using heat circuitry driven by solar cells.

In research previously carried out by the author, the method using a power pack to activate textile samples printed with thermochromic dyes had been used to conduct preliminary investigations into the efficiency of different heat circuit solutions. Set-up H built on the use of this type of set-up and energy source (see Figure 3.21).

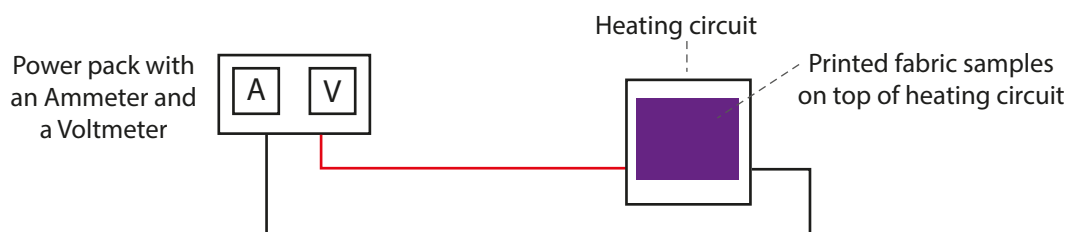


Figure 3.21 Set-up H, powering the heat circuits with a power pack.

This allowed the comparison and validation of the results using the sophisticated heaters investigated within this research against these previous measurements on more rudimentary heating systems. The electrical current was measured and the effect of the colour change in the textile samples monitored and documented as the voltage was gradually increased. The shape, heat spread, and size of the surface that changed colour within the printed fabric samples were observed and measured. Photographs were taken to document the different stages of change that occurred within the textile samples printed with thermochromic dyes.

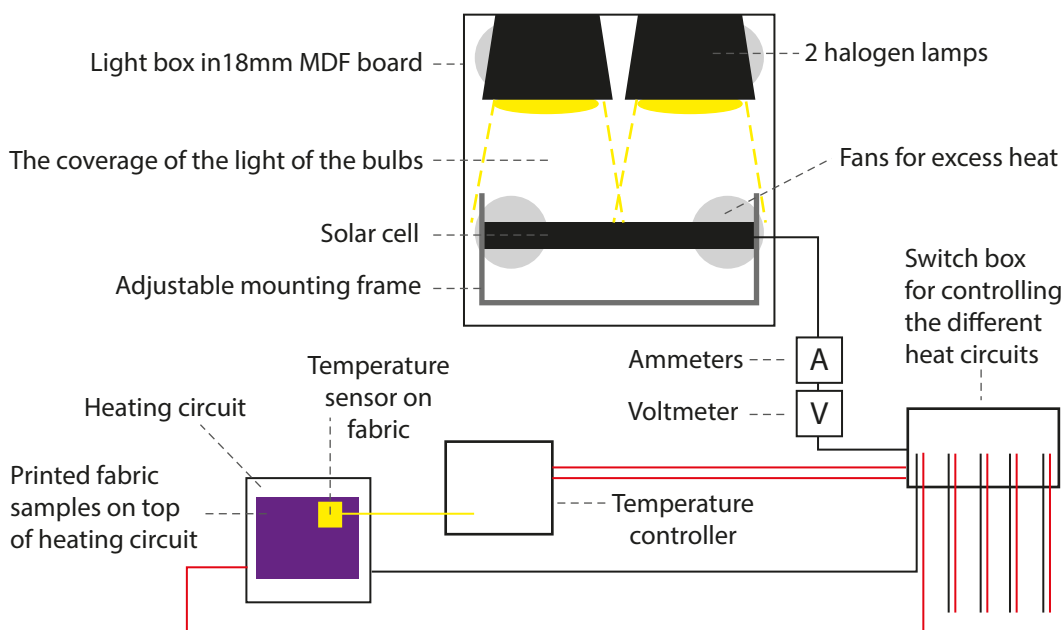


Figure 3.22 Set-up I, powering the solar cell with lamps recommended for the purpose.

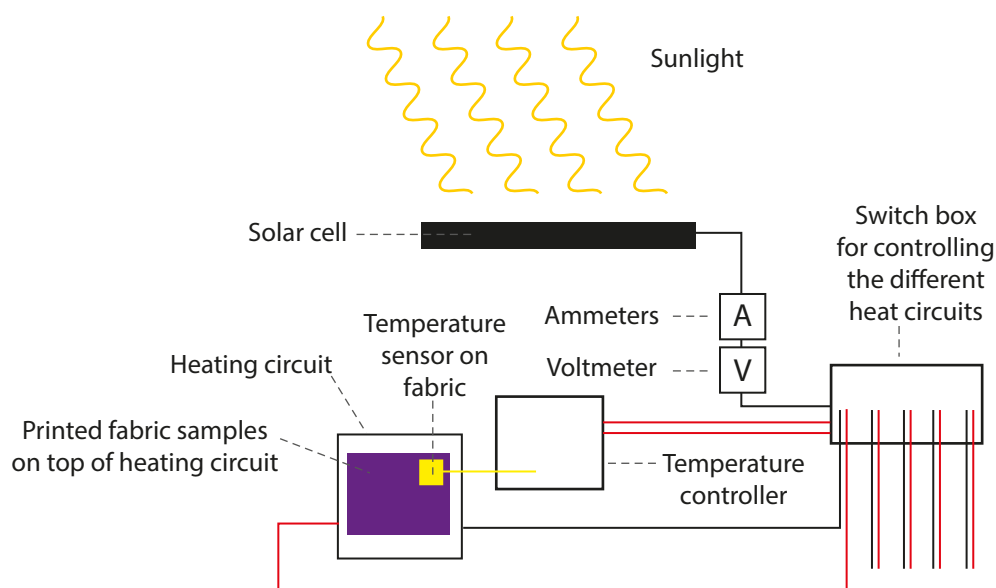


Figure 3.23 Set-up J, powering the solar cell with natural sunlight.

Both a rigid and a flexible solar cell were used in the experiments. The rigid, multi-crystalline solar cells at 10W, were either a 12V BP Solar SX 10U Standard, CA-10/1 cell supplied by Marlec Renewable Power, UK or a MSX-10 Lite, 16.8V cell supplied by BP Solar, UK. The flexible solar cell at 1.2W, was a 12V, 100mA, thin film amorphous silicon photovoltaic cell, supplied by Silicon Solar, US. The devices used as heaters were an external high power 33ohm Meggitt SBCHE 11 CGS resistor, a star-shaped, copper metal plated circuit, soldered with twenty-one, 150ohm (0.65mm x 1.65mm) resistors as well as a glass wafers with nickel and titanium-based, electroplated, parallel-connected microheaters. This last set of circuits was constructed on the basis of a multidisciplinary collaboration with Dr. Wang, Prof. Wilson and PhD student Chandrasekar, in the School of Engineering and Physical Sciences at Heriot-Watt University, UK.

The temperature of the textile samples, heaters, contact surfaces of the textile samples (i.e. glass panes), solar cells and the ambient temperature were monitored using a hand held Eirelec E 5000 thermometer probe, supplied by Eirelec Limited, Ireland. Lux values were measured with a LX1010BS digital luxmeter with a range of 1-100,000 lux, supplied by Dr.Meter, US.

Chapter 4 The sun as a direct activator for sun-screening textiles printed with thermochromic leuco dyes

In this chapter, the reader will find an investigation of the relationship between thermochromic dyes printed on textiles and their interaction with direct solar energy, leading to activation and deactivation of the dye (part I). These investigations were conducted using a direct activation mechanism that may be considered as low-technology. In this context, direct activation means by way of heat from the sun's rays, either directly on the textile or heat from a glass window heated by the sun, or both. The aim of these investigations was to answer the question: does using direct solar activation to activate thermochromic dyes need a different approach in the design process compared to methods currently used for activation, especially the two most commonly used ('traditional' heating mechanisms and body heat)? The investigations in this chapter demonstrate the difficulties encountered in controlling the aesthetic outcome of the printed thermochromic designs when working with a highly uncontrollable parameter such as direct solar activation. In conclusion, compared to working with other currently-used activation methods, working with direct solar activation introduces more parameters and consequently gives the designer less control over the aesthetic outcome.

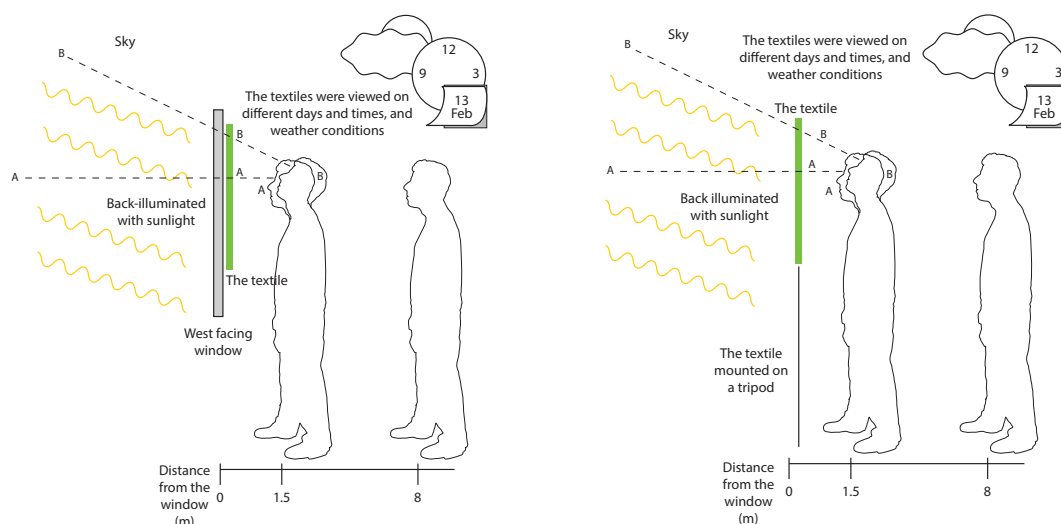
The main contributions to the field of knowledge from the research described in this chapter are sets of 'guidelines' in the form of 'design variables', defined by the author, to expand the aesthetic vocabulary for designers using thermochromic leuco dyes and amendments to descriptors for the 'reversible dynamic pattern', as used in previous research (see 2.2.1). This chapter presents two different levels of design variables as well as amendments to the descriptors. One level concerns activation of the thermochromic dye in general (section 4.5) while the other specifically concerns direct solar activation (section 4.4). Section 4.6 contextualises the findings, giving examples of how a designer, within the design process, could use these design variables. The decision concerning the choice of activator will be guided by the set of more general design variables, which are defined in this thesis as 'amount of thermal energy', 'heating ability', 'time interval/temporal pattern' and 'distribution of heat'. Clarity of the intended activation scenario can be provided for the designer by introducing these design variables at an early stage in the design process. A comparison of the three heating sources (direct solar activation, 'traditional' heating mechanisms and body heat), based on the practical work involving the qualitative, observational methods as described

in section 4.3, the author's many years of experience with chromic materials, and literature review of other designers' and artists' experience in this area, constituted the research material that led to the development of this general set of design variables. The second set of design variables was devised to guide the printmaker practitioner to understand how to achieve more control of the aesthetic outcome when working with direct solar activation. This second set of design variables, defined as 'amount of sunlight', 'time interval', 'temporal pattern', 'contact surfaces', 'ambient temperature' and 'distribution of sunlight' provides information about how direct solar energy relates to thermochromic leuco dyes. The design variables are based on the outcome of the qualitative application of observational methods as described in section 4.3.

Two amendments to the existing descriptors for 'reversible dynamic pattern', defined by Worbin (2010) are proposed (the existing description is $(A B A)$ where A represents the inactive state and B the active state). One amendment is proposed to suit specific applications involving thermochromic dyes that are activated by sunlight. A second, more general amendment for thermochromic dyes is proposed which concerns the colour movement between the 'static' colour states, referred to as states 1 and 2. A new phase is defined within this thesis as the 'transitional colour phase' (T). The conclusion from research described in sections 4.3-4.4 led to two descriptors for reversible imageries created with thermochromic dyes. The first descriptor is used during activation using sunlight $\{A T B_i(s) T A\}$ and the second is used for any thermochromic print activated using an undefined activation method $\{A T B T A\}$. The first new descriptor informs designers that the dynamic nature of the colour change is dependent on the weather [(s) sky condition] when using direct solar activation. Worbin's descriptors for reversible dynamic patterns inform printmakers that working aesthetically with thermochromic dyes requires a wider way of thinking about colour compared with the more 'traditional' static patterns. However, rather than merely considering a move from one 'specific' colour to another, the amendment suggested in this thesis informs the designer that he/she also has to consider the colour outcome during the *movement between* the two more 'static' colours, during activation or deactivation of any thermochromic dye.

The experimental work presented in section 4.3, which is analysed in sections 4.4 and 4.5, was carried out using a set of 55 printed samples, which were all observed both using an indoor set-up A as well as an outdoor set-up B (see Graphic 4.1-4.2). The set-

ups for the observation were devised in a detailed, controlled manner, including for example the specific positions of the observer and sample so that light passed through the textile sample as well as for a distance between observer and samples. These parameters involved were used to establish a controlled framework for the observations, due to fact that the data obtained were defined based on the interpretations of the observer.

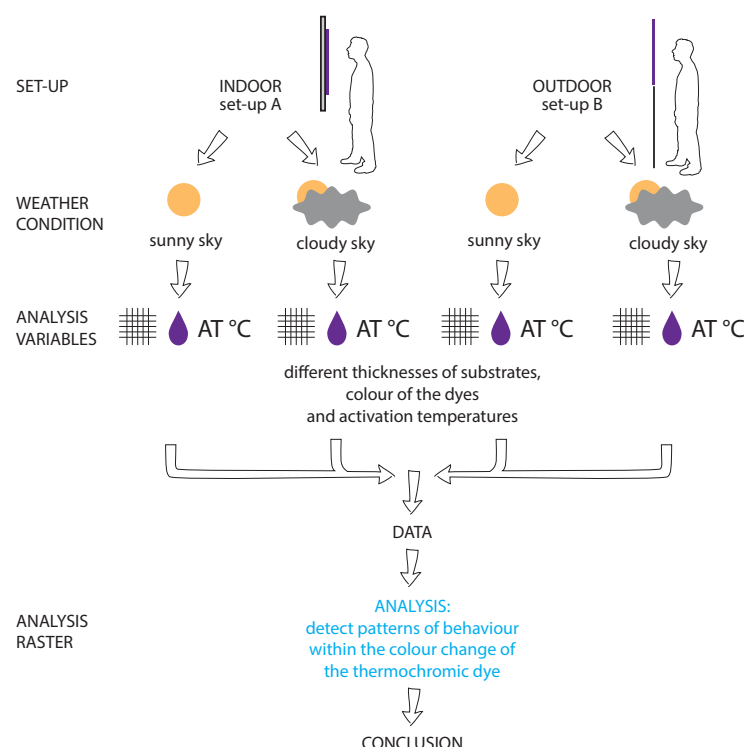


Graphic 4.1-4.2 Set-ups A and B, when observing the textile samples.

Four selected materials, in a variety of thicknesses, were individually printed with each of seven selected colours, respectively, resulting in 28 different samples. An additional group of samples were printed with a multi-coloured imagery using the selective colour palette. 40% of the observed samples were printed using only leuco dyes, while the other 60% were printed in combination with permanent pigments (see Table 4.1).

The majority of the samples were observed both indoors as well as outdoors. Additionally, each sample (both indoor and outdoor) was observed during the two defined daylight conditions, sunny and cloudy sky (for definition of sky conditions see section 3.7.1). An evaluation of the percentage of cloud coverage of the sky as well as measurements of the prevailing lux values were carried out during each individual observation, to affirm the definition of the sky conditions. A representative selection of the collected data, from the extensive amount of data gathered during more than 500 observations, is presented in the thesis. The data presented (including excerpts from the observation log and photographs) were selected to illustrate and support the arguments of the analysis. The collected materials from all observations were divided into three groups during the analysis: samples printed with dyes with activation temperatures lower or equal to the ambient temperature (section 4.3.1), with activation temperature higher than

the ambient temperature during sunny (section 4.3.2), and the latter under cloudy sky conditions (section 4.3.3). The data were analysed on the basis of a framework to detect patterns of behaviour within the colour change of the thermochromic dye when different thicknesses of substrates, colour of the dyes or activation temperatures were used, in relation to the variables investigated, namely sunny or cloudy sky, and indoor (using a contact surface of a windowpane) or outdoor (see Graphic 4.3).



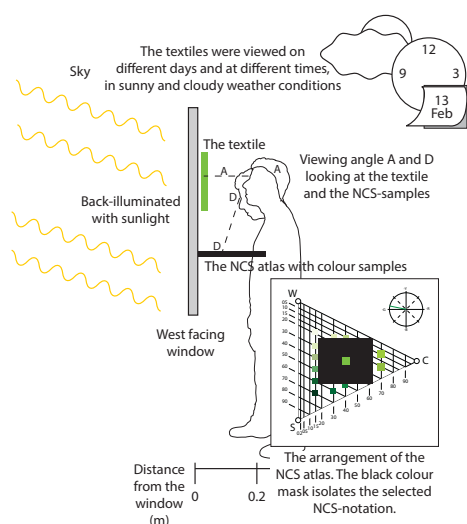
Graphic 4.3 The process of analysis of the data from set-ups A and B.

Scientific, quantitative methods of monitoring temperature curves, conducted using a hand held Eirelec E 5000 thermometer probe were used for parts of the visual data analysis to cross-reference the results. The perception of a more prolonged colour change with lighter printed materials, compared to darker materials, was confirmed by measuring the temperature curve of the various coloured samples (see Table 4.6). Temperature curves were also developed to compare the heating ability of the windowpane, the air adjacent to it, and the fabric surface touching the windowpane, to understand the effect on the thermochromic dyes of contact with glass (see Table 4.5).

Additionally, this chapter presents and discusses the theory of mixing thermochromic dyes. Written and graphical explanations of the principles of colour mixing using leuco dyes in practice are given to address an area that had been

inadequately discussed prior to this thesis. Section 4.1.1 presents a set of graphics, defined by the author, supported by explanations of the mixing principles for thermochromic dyes, both with leuco dyes on their own as well as combined with permanent pigments, providing practical guidelines for the designer. The graphics illustrated in Figures 4.6 and 4.7 are suggested as a communicative tool for designers when working with leuco dyes, for example when conveying the spectrum of colour change of the dye within a design to another person.

During the phase of research that defined the dye recipes for the final printed colours, it was concluded that the textile printmaker practitioner also has to consider the activation temperature (AT) and supplier (in this case Matsui or LCR Hallcrest) of the thermochromic dye. This conclusion was based on observations that dyes of the same colour with different activation temperatures and from different suppliers of the same colour were perceived as providing different nuances in their properties. Recognising this feature is important in order for the designer to achieve the desired aesthetic outcome. The visually observed difference in the colour outcome of the printed samples (selection of samples, see Table 4.1) was analysed using the method of qualitative measurements by plotting the perceived colour outcome in the colour triangle and the colour circle of the Natural Colour System (NCS) (see section 3.2.4 as well as Graphic 4.4). Six of the twelve plotted samples are presented in the thesis in Figures 4.10 and 4.11 to exemplify such differences.



Graphic 4.4 Set-up A2 used for plotting the perceived colour outcome.

4.1 Establishing a restricted colour palette

The following section is aimed at informing the reader of the aesthetic development of the pre-set colour palette. The restricted colour palette was established in the design brief in the initial phase of the design process (see section 3.3.1). The design brief was set as a framework for the intended textile print design process. The colour palette also turned out to be a means for developing an understanding of the variation in visual colour outcome of textiles printed with thermochromic dyes using dyes from the two suppliers, as well as with different activation temperatures. In the pre-set aesthetics, it was defined that the colour change within the textiles printed with thermochromic dyes should be visually quite obvious. The colour palette was designed, using general textile print design methods, as described in section 3.5.3. The colour changes were developed to proceed from a more energetic to a more calm expression. The colour palette aimed to contain a group of colours that would work well together. The colour palette (yellow, orange, magenta, purple, blue, blue-green and mint-green) was developed through self-expression based on the image boards with collected inspirations taken from butterflies and a sunny, blue sky, and with the theme keyword ‘change’. Colourful butterflies were chosen as inspiration, since the species are characterised by a variety of colourful hues, leading to the image of a colourful butterfly in flight with a blue sky as a backdrop. The sunny, blue sky was chosen since this was considered to be the ideal sky condition to activate the textiles printed with thermochromic dyes. The calmer colour expression was later renamed ‘sky colours’.



Figure 4.1 Image board for the butterfly inspiration.

The image boards, a version edited from the wider content that had been selected from both primary research, such as drawings and photographs by the author of real butterflies and sunny skies, as well as from secondary research from different royalty free images of butterflies and sunny skies, acted as a colour-referencing tool for the development of the colour palette (see Figure 4.1). The initial colour selection was thereafter refined through sampling (see Figure 4.2) and then finally mounted on two colour boards (see Figure 4.3), one focusing on the section of inactive colours and one for the active colours.



Figure 4.2 Colour sampling in the sketchbook, to reach the pre-set colour palette.



Figure 4.3 The two colour boards.

4.1.1 *Mixing principles of thermochromic leuco dyes with permanent pigments*

The extensive colour mixing carried out, as described throughout this thesis, resulted in the construction of illustrations (Figures 4.4-4.7) to explain the mixing principles for thermochromic leuco dyes, both purely for leuco dyes as well as combined with

permanent pigments. These illustrations provide practical guidelines for the designer. The textile print design process used in this research was in most ways similar to the process generally used for design, up to the point of colour mixing. However, a different approach to the ‘colour phase’ of the process became necessary, in terms of how to approach the colour mixing. As described in section 2.1.1, thermochromic leuco dyes become colourless when heated and, by mixing with permanent pigments, it is possible to provide a change from one colour to another. (Christie, 2013, pp.8-14) Written and graphical explanations of the practicalities of mixing leuco dyes has been an area requiring development in the literature. Experience has demonstrated that each new designer, interested in the use of thermochromic dyes, has had to develop an understanding without relevant guidance. The approach was developed based on conclusions from theoretical considerations as well as the author’s extensive experience of practical work using the leuco dyes (including hundreds of samples from this research).

‘Colour state 1’ (see scenario 1 in Figure 4.4) is defined as the ‘inactive colour state’, which in scenario 1 represents the visible thermochromic colour, when leuco dyes are used alone. In scenario 2 (Figure 4.4), when the dye is mixed with permanent pigments, colour state 1 is the visible effect of mixing the two. ‘Colour state 2’, defined as the ‘active colour state’, is in scenario 1 represented by the colour of the fabric substrate, since the dye is more or less completely colourless. In scenario 2, the visible colour of colour state 2 is the colour of the permanent pigment in the mixture.

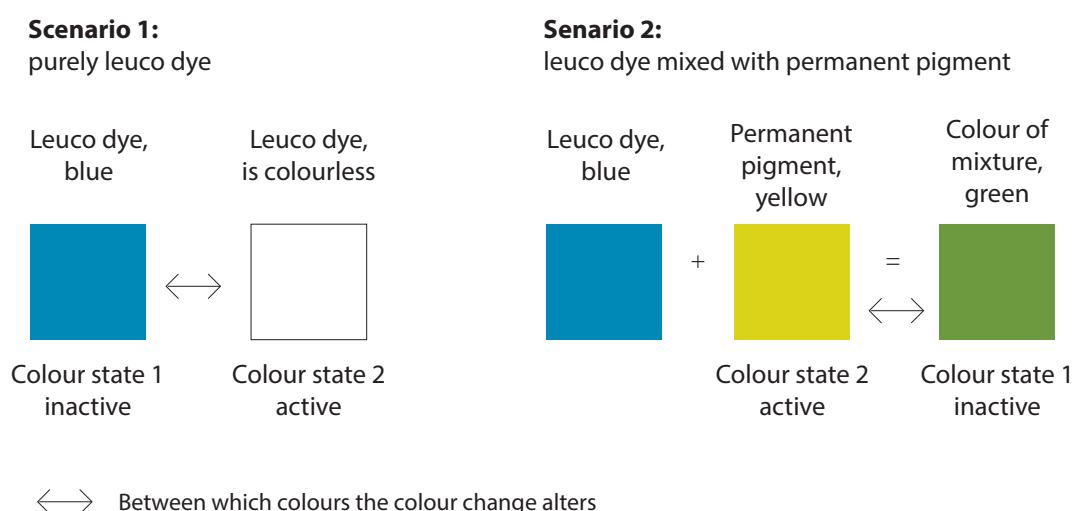


Figure 4.4 Graphic of two scenarios in heating thermochromic leuco dyes; leuco dyes alone as well as mixed with permanent pigments.

Mixing leuco dyes with permanent pigments involves the principles of subtractive mixing², as with the normal mixing of permanent pigments. Obtaining the intended printed colour depends on the possibility to find the required balance between the different components of the mixture, for example in selecting the pigments and binders in the print paste when printing direct style³. Mixing thermochromic dyes with permanent pigments requires that the designer needs not only to establish the balance between the relative percentages of dyes and permanent pigments to provide the desired inactive colour (state 1), but also the desired colour of state 2, the colour of only the permanent pigment, when the leuco dye is active. For example colour state 2, as illustrated in Figure 4.4, appears green if blue leuco dyes are mixed with yellow permanent pigment. Colour state 1 will then appear yellow (the colour of the permanent pigment). The range of hues that is feasible when mixing leuco dyes and permanent pigments, in terms of the colour changes possible is restricted considerably by the rules of subtractive mixing. In order to obtain a pronounced colour change from state 1 to 2, it is generally the case that colour state 1 requires to be 'darker' than colour state 2, meaning that the leuco dye needs to be 'darker' in hue compared to the permanent pigment. (Berzina, 2004, pp.183-184) Additionally, there is a limitation in the variations of off-shelf thermochromic colours available from existing suppliers compared to permanent pigments. More specific colours can often be provided by the suppliers, if chemically possible, through special orders but at a notably higher price. (LCR Hallcrest, n.d.; Matsui, n.d.)

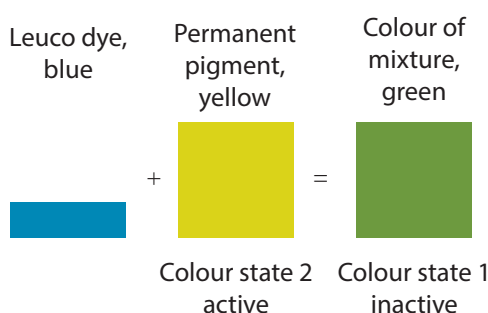
Changes in the ratio between the components in the dye recipe of leuco dyes mixed with permanent pigments can provide a range of hues, as with traditional subtractive mixing. However, there are two ways to approach the variation in colour outcome in designing, since there are two visible colours (states 1 and 2). The designer can decide either to affect colour state 1 only or both of the colour states. As illustrated in examples 1 and 2 in Figure 4.5, the green hue (colour state 1) will change when there is a decrease or increase in the percentage of the blue leuco dye in relation to the yellow permanent pigment. The green hue will appear lighter and more yellow as the amount of blue dye is decreased or the yellow dye is increased. Alternatively, the green hue will appear darker

² The method of subtractive colour mixing with pigments applies when light is absorbed by the colour, in contrast to the opposite method of additive colour mixing (used when mixing light). A subtractive mix of all pigment colours will in theory create black. (Pipes, 2003, pp.148-149)

³ Direct style: printing method often associated with one or more positive images printed with permanent pigments. (Kinnersly-Taylor, 2011, pp.70-71)

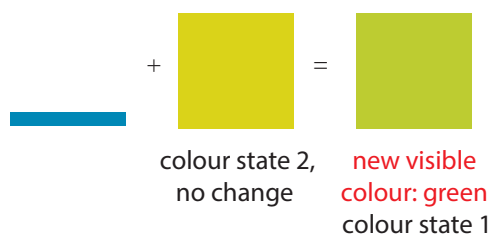
and more blue-green if the amount of blue is increased or yellow decreased⁴. In both examples the yellow colour in state 2 will stay the same. This feature will also be observed if the hue of the leuco dye were altered, with the permanent pigment kept the same (as illustrated in Figure 4.5, example 3 when the blue leuco dye is changed to a red leuco dye). However, both colour states will change if the hue of the colour of the permanent pigment is altered, even if the leuco dye is kept the same. As illustrated in example 4 in Figure 4.5, colour state 2 appears orange rather than yellow and colour state 1 appears more grey-brown, compared to the original dye recipe, due to an amount of mixed red permanent pigment together with the original yellow permanent pigment.

Original dye recipe



Example 1:

decreasing the percentage of leuco dye



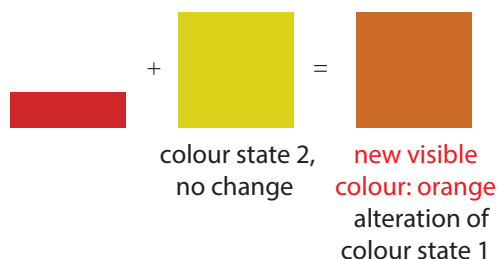
Example 2:

increasing the percentage of leuco dye



Example 3:

changing the hue of the leuco dye



Example 4:

changing the hue of the permanent pigment



Figure 4.5 Illustration of changes in the colour outcome in colour state 1 and 2.

⁴ The exemplified changes are carried out with the ratio between the leuco dye and the permanent pigment, not in the ratio between the dye and the binder or the pigment and the binder. The latter would alter the colourfulness of the colours, which would provide a possible change within both colour states, as is exemplified in example 4 in Figure 4.5.

These examples illustrating the principles of mixing leuco dyes with permanent pigments have, for reasons of avoiding complexity, only taken into account up to two variables (one leuco dye with a specific activation temperature and a permanent pigment). Mixing more than one leuco dye with different activation temperatures can provide more than two colour states. Depending on the number of different activation temperatures used, several colour states can be obtained. For example, as illustrated in Figure 4.6, mixing dyes with three different activation temperatures provides the possibility for four colour states. The increase in the number of dyes with different activation temperatures thus results in a notably more complex system, but offers the designer additional colour outcome as well as imagery possibilities.

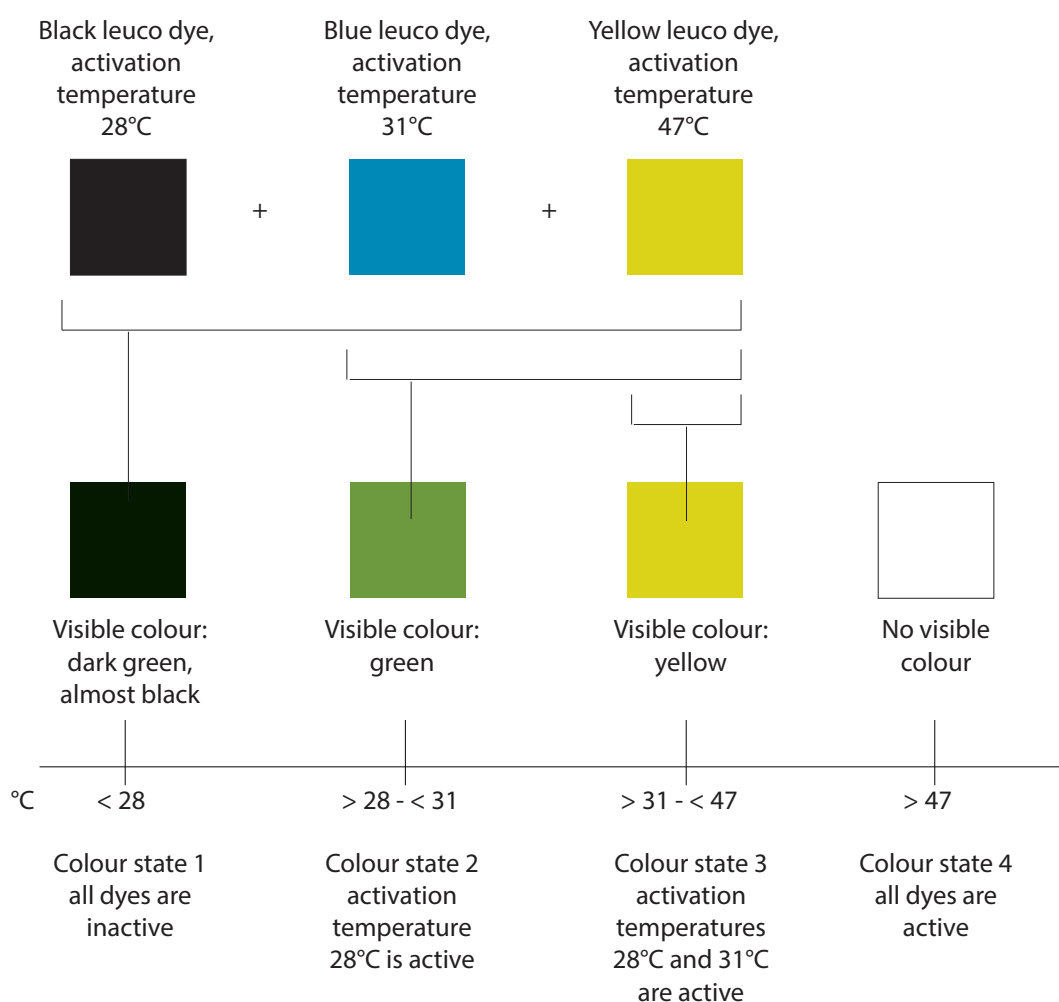


Figure 4.6 Illustration of mixing several thermochromic leuco dyes with different activation temperatures.

Dyes with the same set of activation temperatures, combined with a permanent pigment would also provide four possible colour states (see Figure 4.7). The visible

colour outcome in the different colour states will, as with the example with two colour states, be dependent on the colours of the leuco dyes as well as the permanent pigment.

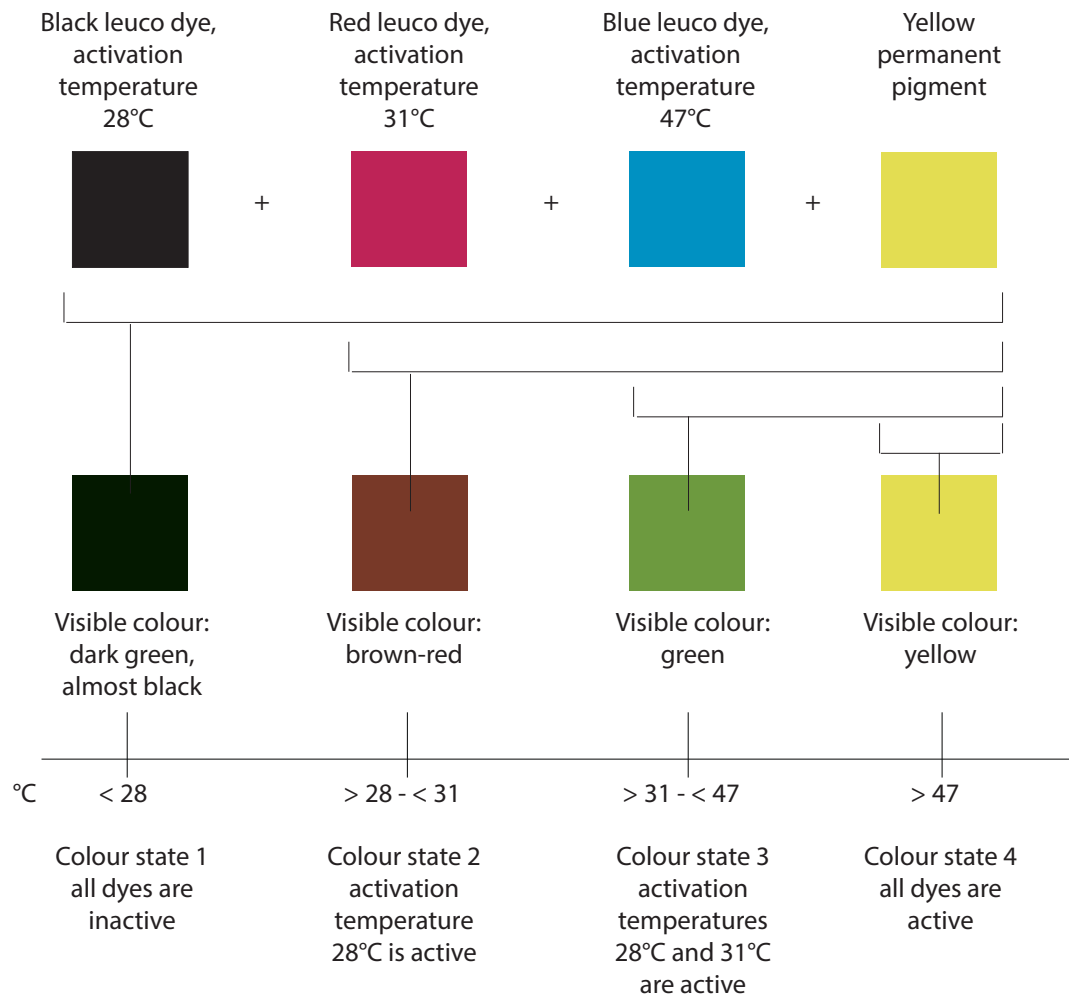












Figure 4.7 An illustration of a mixture using several thermochromic leuco dyes with different activation temperatures and with a permanent pigment.

The graphics illustrated in Figure 4.6 and 4.7 are additionally suggested as a communicative tool for designers when working with leuco dyes, for example when conveying the spectrum of colour change of the dye within a design to another individual. Only one other publication that discusses this issue has been identified. Kooroshina (2013a) presented a laboratory exercise for design teachers to convey practically the principles of mixing the leuco dyes to students. The methods developed in this thesis, in terms of the illustrations of the principles of mixtures, work well in conjunction with the work of Kooroshina.

4.1.2 *The pre-set colour palette*

This section describes the method used for colour matching in devising the colour palette. The two colour boards, see section 4.1, Figure 4.3, defined the final hues, tints and colour proportion of the colour palette. The palette, see Figure 4.8, informed by the colour boards, was then matched within the ‘colour’ phase of the textile print design process, through screen-printing samples using the leuco dyes as well as pigments, until a visually similar colour outcome was reached (see Figure 4.9).

The energetic colours					The sky colours				
									
C 10	C -	C -	C 50	C 70	C 70	C 100	C 65	C 10	C -
M -	M 50	M 100	M 100	M 100	M -	M -	M 30	M -	M 50
Y 100	Y 100	Y -	Y -	Y 20	Y 60	Y 50	Y -	Y 100	Y 100
K -	K -	K -	K -	K -	K -	K -	K -	K -	K -

C, M, Y, K = the values in % of cyan, magenta, yellow and black for print

Figures 4.8 The final pre-set colour palette, with one set of energetic colours and one set of calm colours.



4.9 Examples of fabric samples during the process of matching the colours of the printed textiles with the colours of the pre-set colour palette in the sketchbook.

The energetic colours of the colour board (see Figures 4.8) represented the inactive state of the printed thermochromic dyes (colour state 1 - when the textiles were cold). The purpose of the more energetic colours was to create an expression with positive energy and feelings, provided through the use of a higher level of chromaticness (colourfulness). The keywords describing the sub-group of the energetic butterfly theme were: ‘happy’, ‘alive’, and ‘vibrant’. The idea behind the energetic

colours was that bright and positive colours liven up the mood when the sky is grey and the weather outside is dull. The colour proportions were used to provide a balance between the hues, so that one colour did not dominate excessively. The colour selection used complementary colours to accentuate these attributes (such as purple and yellow, and to some extent, blue-greens and magenta).

The sky colours, of the colour board (see Figures 4.8) represented the active state of the printed thermochromic dyes (colour state 2 – when the textiles were heated). The aim of the calmer colours was to represent a blue cloudless, sunny sky, through the use of lower chromaticness and a more blue-white monochrome expression. The keywords describing the sub-group of the sunny and sky blue theme were ‘sky’, ‘sun’ and ‘fresh’. The idea behind the sky colours was that the blue colours did not dominate the expression, but drew attention towards the sunny weather. The blue was chosen as the colour of the sky a sunny day, and for its calming and fresh characteristics. The use of smaller amounts of yellow and orange was chosen as symbolic colours of the sunlight, as well as to create an effect contrasting with the blue.

The developed colour palette consisted of colours containing both traditional permanent pigments and thermochromic dyes. The yellow (Y) and orange (O) were developed using permanent pigments. The yellow and the orange were therefore not temperature sensitive, appearing the same regardless whether the printed textile is warm or cold, which was considered appropriate since they were represented in both colour boards. The magenta (M) was developed using a thermochromic dye, resulting in a magenta colour in state 1 (when the textile was cold) and colour that was either more or less the substrate colour or a very light magenta when the textile was warm (state 2). The remaining colours were developed using pigments combined with thermochromic dyes. These hues provided a colour change from the hue (state 1) that was created when the dyes and pigments were mixed, to the hue (state 2) of only the pigments. The light purple (LP) changed to a lighter tint of the blue (LB) when the printed textiles were heated, and the dark purple (DP), the mint-green (MG) and the blue-green (BG) all changed to similar darker shades of the blue (DB).

The colours based on dynamic dyes (M, LD, DP, MG and BG) were obtained by mixing three different versions of thermochromic dyes: the 27°C Matsui as well as 31°C and 47°C Hallcrest. Initially the five colours (M, LD, DP, MG and BG) were mixed using 27°C Matsui dyes, some combined with pigments (LD, DP, MG and BG).

Secondly the 31°C and 47°C Hallcrest dyes were used aiming to provide the same hues and tints as the 27°C Matsui dye samples.

4.1.3 Using dyes from different suppliers and with different activation temperatures

This section demonstrates how the process of defining the dye recipes for the final printed colours led to an understanding that the textile printmaker practitioner needs to consider the activation temperatures (AT) and supplier (Matsui or LCR Hallcrest) of the thermochromic dyes in order to achieve the desired colour outcome.

Initial test samples indicated that samples printed with the same dye recipes but with different makes of the thermochromic leuco dye, as well as the same make of dyes but with different activation temperatures, resulted in samples with slightly different colour outcomes. In the tests aiming to achieve visual matching of each specific colour, the amount of thermochromic dye was kept constant, to provide an understanding of the impact of the two makes and the different activation temperatures on the colour outcome. The printed samples, see Table 4.1, were compared using the indoor observation set-up A, see section 3.7.2 and Graphic 4.1 and the NCS visual colour identification method, set-up A2, see sections 3.7.3 and Graphic 4.4.

Table 4.1 The selection of printed samples (supplier, AT, colour) used in investigation of colour outcome.

Supplier	AT	Blue (B1)	Black (B2)	Red (R)	Magenta (M)	Light purple (LP)	Dark purple (LP)
Matsui	27°C				X	X*	X*
LCR Hallcrest	31°C	X	X	X	X		
LCR Hallcrest	47°C	X	X	X	X	X*	

*The samples were duplicated on both silk-viscose satin and silk-viscose velvet.

Notable differences in whiteness value (W) and chromaticness value (C) were observed in the colour outcomes, when textile samples printed with the base colours were observed in the inactive colour (state 1). The colour outcomes of the printed samples were plotted in the NCS colour triangle and the NCS colour circle, as described in section 3.2.4. Initial silk-viscose satin samples were mixed using thermochromic dyes, blue (B1), black (B2), magenta (M) and red (R), with activation temperatures 31°C and 47°C, from LCR Hallcrest. The thermochromic dyes (B1, B2, M and R) were mixed with the same ratio of standard pigment binder (for dye recipes see Appendix A). The largest difference in the perceived colour outcome was observed between the red 31°C and 47°C Hallcrest dyes. The 31°C sample had a whiteness value, as well as a

chromaticness value, which was notably *lower*, than the 47°C sample. The 31°C magenta Hallcrest sample, in contrast to the red sample, provided a notably *higher* whiteness value, compared to the 47°C magenta Hallcrest sample. The two magenta samples gave the same chromaticness value. Also the 31°C blue Hallcrest sample provided a slightly *higher* whiteness value, as well as chromaticness value, compared to the 47°C blue Hallcrest sample. The 31°C black Hallcrest sample provided a slightly *higher* whiteness but a slightly *lower* chromaticness value, compared to the 47°C black Hallcrest sample.

The notable differences in whiteness value (W) and chromaticness value (C) were further observed when samples mixed using the same dye recipe, but with different activation temperatures as well as dyes from the two suppliers (Matsui and LCR Hallcrest). The colours were observed in the inactive state (state 1) of printed silk-viscose satin samples. The colour outcome of the textile sample printed with magenta Hallcrest 31°C had the highest whiteness value (see orange mark in the colour triangle, in Figure 4.10). The sample printed with magenta Hallcrest 47°C, measured the lowest whiteness values (see red mark in the colour triangle in Figure 4.10). In contrast, the magenta Matsui 27°C, which has the lowest activation temperature measured between the two LCR Hallcrest dyes (see dark purple mark in the colour triangle in Figure 4.10).

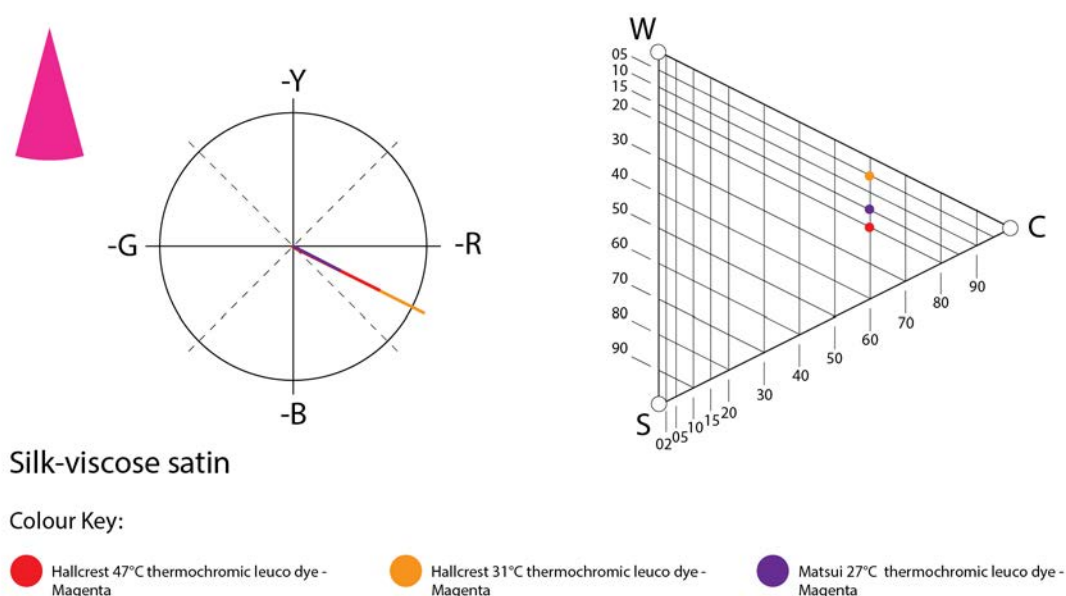


Figure 4.10 NCS-mapping of textile samples printed with thermochromic leuco dyes, carried out indoors in set-up A2 in sunny sky condition.

Further tests of samples printed with light purple (LP), which incorporated a blue permanent pigment and a magenta thermochromic leuco dye, included silk-viscose velvet substrates as well as the silk-viscose satin to see if the result would differ if printed onto another material thickness. The samples printed using the 47°C LP were perceived in some cases to have higher whiteness values (W) and chromaticness values (C) but in a few cases the values were lower, compared to the two lower activation temperature dyes. The two samples printed light purple with the 47°C Hallcrest magenta dye appeared, in addition, *bluer* compared to the samples both printed dark and light purple with the Matsui magenta thermochromic, 27°C. This meant that the sample printed with the dark purple Matsui 27°C (the dark purple line in the NCS colour circle) was perceived as having a smaller percentage of ‘blue’ than was perceived in the light purple Hallcrest 47°C (the red line in the NCS colour circle) (see Figure 4.11).

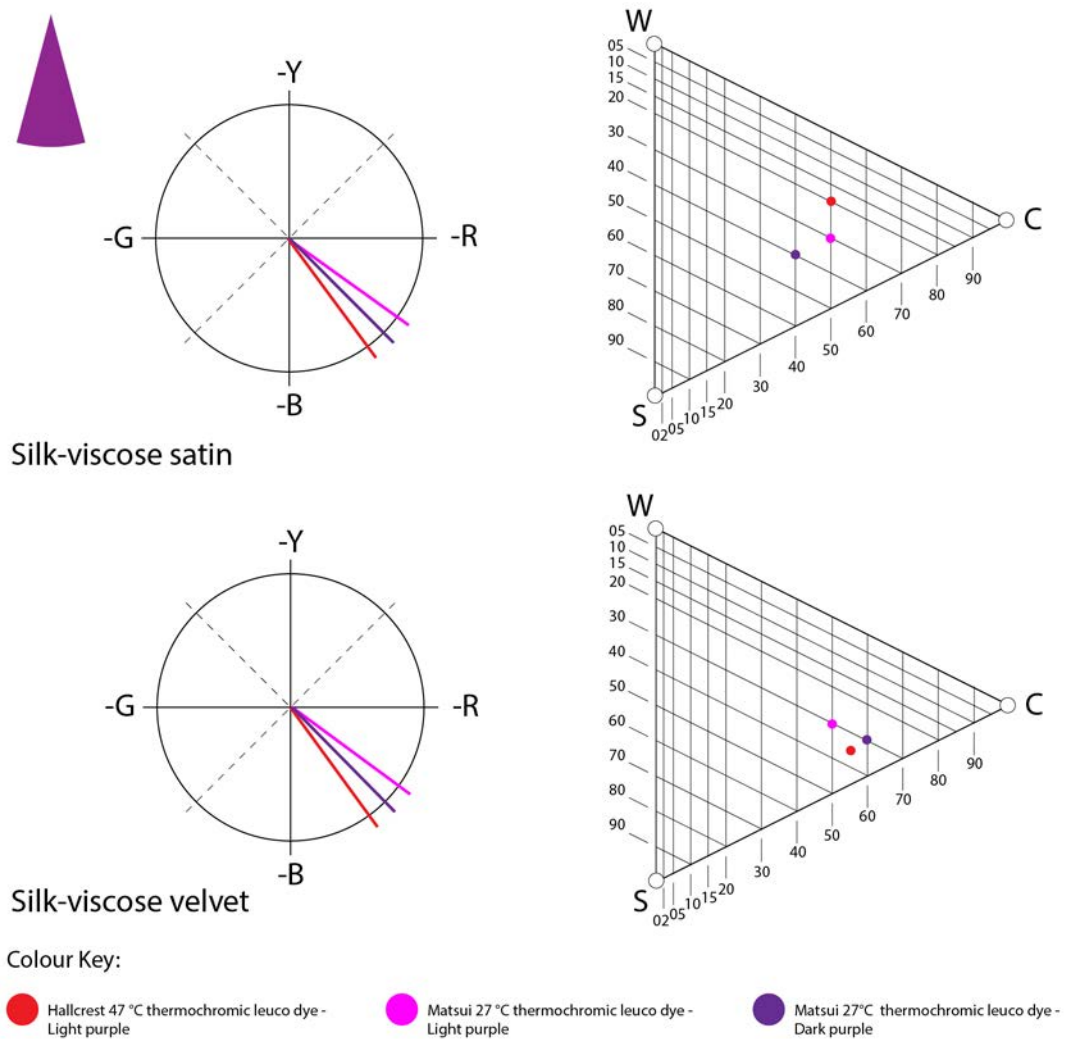


Figure 4.11 NCS-mapping of textile samples printed with thermochromic leuco dyes, carried out indoor in set-up A2 in sunny sky conditions.

The plotted NCS notations showed that the thermochromic dyes with different activation temperatures and from different suppliers behaved differently when mixed to the same percentage with standard pigment binder. The results demonstrated that the different dyes led to a difference in, for example, perceived colour tones. A notable result of the investigation was that dyes with different activation temperatures, supplied by the same supplier, did not behave uniformly. This means that textile printmaker practitioners, when working with dyes with different activation temperatures, should, from a mixing point of view, consider each as an individual dye. The results demonstrated no direct relation between the activation temperature and the perceived level of whiteness (W) or chromaticness (C).

4.2 Defining the selection of substrate fabrics in relation to the aesthetic design brief

This section describes the selection of textile substrates that were used within the investigations reported in this thesis. The selection was carried out on the basis of the aesthetics of the pre-set design brief (see section 3.3.1). Additionally, this section describes how the investigation preceding the selection of substrates resulted in the discovery of an additional type of colour change when printing with pigments onto a particular silk-viscose velvet fabric.

The design brief addressed the aim of using textile materials with properties that aesthetically ‘enhanced’ the printed surface when the sunlight penetrated the fabric (see section 3.3.1). The section on material properties was included in the design brief so that the relationships between the sunlight, the substrate material and the colour outcome would be taken into consideration. The design brief further considered the thickness of the substrate material, through an investigation of its effects on the colour change of the thermochromic dye.

Using set-up A, Figure 3.11, as defined in section 3.7.2, an initial set of indoor sunlight observations was carried out using a broad selection of textile samples (see Appendix C). The aim of the initial observations was to provide an understanding of the variety of aesthetic colour and fabric related effects that the sunlight could create. The observations of the 36 selected samples were carried out in both sunny sky and cloudy sky, so that comparisons between the two broad sky conditions could be made and conclusions of the effect of the sunlight could be drawn (see examples in Table 4.2).

Table 4.2 Excerpts from the observation log of the 36 samples, of observations of what the sunlight brings to the substrate fabrics.

Date/Time	Weather	Viewing distance	Comment (regarding the different samples; #)
Indoor set-up A 26-10-2010 1.30pm	Cloudy sky	0.5-1.5m & 8m	Sample # 17: (non-woven polyester) With a lighter background (the sky) the non-woven sample appears more uneven; the cluster of fibres and the areas containing less fibre become more obvious. With a darker background (house or greenery) the non-woven sample appears more even, which in turn creates a perception of a more even print result.
Indoor set-up A 26-10-2010 1.30pm	Sunny sky	0.5-1.5m	Sample # 21: (silk-viscose satin) The printed colour of the sample provides increased chromaticness during sunny sky compared to cloudy sky, which is interesting. The silk-viscose satin is perceived more even as the non-woven sample.

The samples provided a range of hues printed with a variety of permanent pigments and dyes, as well as thermochromic leuco dyes. The selection for the initial study included a broad variety of textile materials with diversity in thickness, to provide initial information on the impact of the quality of the material on the aesthetic expression. For analysis of the observed printed fabrics, the materials were divided into the following four groups relating to the translucency of the fabrics: see-through, semi see-through, semi heavy and heavy fabrics. The substrate was analysed in terms of how even the fabric structures appeared as well as the expression of the printed colour when the fabric was penetrated with sunlight (see example of silk-viscose sample #21 in Figures 4.12-4.13).



Figure 4.12 (left) Observed silk-viscose sample #21 during cloudy sky condition. Figure 4.13 (right) The same sample during sunny sky condition. The sample provided increased chromaticness and an even printed surface when the sky condition altered from cloudy to sunny.

The substrate materials that resulted in an enhancement of the aesthetic colour outcome, as well as providing an aesthetic balance between the material structure of the substrate and the colour expression, were selected as the final substrates to proceed with, as explained in section 3.3.1.

Thin cotton cheesecloth, cotton muslin, light polyester chiffon, silk chiffon, silver-grey plain polyester weave, nylon monofilament weave, as well as transparent polyester monofilament weave, were materials that had a see-through quality. The more open structures appeared to result in printed colours with less saturation, especially when observed against a lighter background, such as the sky. The open structure also appeared to result in a less even result when printed with pigments. In some instances, the result was improved with the use of a backing fabric when screen-printed. However, some pigment-printed open structures still resulted in an uneven print. The effect, which is due to excess ink settling within the open structure, became more noticeable when sunlight shone through the samples. This effect was most visible within the nylon weave structure. A potential solution to the problem of excess ink within the open structure could be to use disperse or reactive dyes, as appropriate, for producing permanent colours on these materials. However, the present commercial leuco dyes are essentially pigments, in that they are required to be attached to the surface of the fibres using a binder. There is research in progress at Heriot-Watt University, as explained further in section 2.1.3, into printing with thermochromic dyes using inkjet technology, but the findings are still at an early laboratory stage. (Christie, Shah and Wardman, 2009, p.5) The substrate that provided an enhanced material quality when the sunlight passed through and also when printed with pigments and/or thermochromic dyes was the thin silk chiffon. This material was perceived to provide a slightly 'glittering' or 'sparkling' effect. This effect was noticeable when sunlight penetrated both the printed and unprinted samples. The glittering/sparkling effect appeared to provide an added quality to the aesthetic colour outcome. The material was also considered to act as a good substrate material for the printed coloured surface. The silk chiffon achieved a soft and fairly even printed surface, when the sunlight passed through it, appearing dull and flat. The problems of excess dye in the more open weave structure had initially been partly solved with the use of a backing fabric, but the problems reappeared in later tests. For this reason, and as it did not adequately display the colour change, the silk chiffon was finally excluded. The cotton muslin and the cotton cheesecloth provided duller colour expressions, compared to

the silk-viscose chiffon, and so were not selected for further investigation, even though both the materials also were printed quite well with pigments.

The second group consisted of the following semi see-through materials: T77 print mesh, lightweight silk, non-woven polyester, silk-nylon stocking and woven polyester. Compared to the more opaque fabric substrates, the semi see-through fabrics behaved quite similarly, in terms of colours, to the see-through fabrics. Some of the pigment and/or thermochromic dye printed structures provided the same issues with excess ink in the open weave structure, especially the T77 print mesh. These surfaces were uneven and any slightly unevenly applied ink showed up significantly when the samples were back-illuminated. The more solid fabrics within this group, such as the polyester and lightweight silk, behaved more similarly to the third group (the semi-heavy fabrics), but the colours were perceived as more 'washed out' when back-illuminated due to the thinner fabric quality. It was decided to not continue working with any of the materials within this group, on the basis that the materials did not provide any additional unique qualities in their evaluation.

The third group, consisting of a semi-heavy plain polyester-viscose weave, heavier acetate satin and a similar silk-viscose satin, were all virtually opaque materials. The thickness of the materials was sufficient to provide a printed colour result that was perceived as chromatic and even. The polyester-viscose showed a slightly more uneven structure, compared to the other two, when the sunlight was penetrating the fabric. The polyester-viscose also let through slightly more sunlight because it was the thinnest material within the group. The silk-viscose satin provided an interesting shine and structure to the surface when the samples were back-illuminated at a viewing distance of 1-1.5m. It was the same 'glittering' expression that had been experienced with the silk chiffon. When viewed with sunlight passing through, the printed colours of the satin fabrics appeared to increase in saturation. All of the semi-heavy fabrics were taken forward since the materials were judged to provide sufficiently enhanced qualities as well as meeting the aesthetic material brief.

The fourth group consisted of the following non see-through heavy fabrics: silk-viscose velvet, cotton corduroy, cotton velvet, crushed polyester velvet, mohair, natural fibre wadding, polyester nonwoven felt, polyester fibre wadding, soft polyester and velour. The silk-viscose velvet was the only material that clearly stood out from the others. It provided the same interesting shine and structure to the surface material when

back-illuminated as the silk chiffon and the silk-viscose satin. The silk-viscose velvet samples also provided an additional interesting colour change involving an intensity of chromaticness within the surface expression when it was viewed at different angles, as well as an almost organic, ‘scale-like’ surface from enlarged butterfly wings (see Figures 4.14-4.16).



Figures 4.14 and 4.16 (left and right) The ‘organic’ surface expression of the printed silk-viscose velvet. Figure 4.15 (centre) Same sample mounted onto a windowpane during cloudy sky condition.

‘The chromatic value of the textile surface differs, depending on viewing angle, from barely showing (only dots of magenta) to a strong magenta colour. The illusion seems to depend on if the samples was viewed at right angles to the fabric in the direction of the pile (high chromaticness), or facing the short end of the fibres (low chromaticness). In parts of the folded fabric, the magenta colour appears saturated in the shaded pleated areas (it gave tendencies towards as if radiant with coloured light). Parts of the folds are perceived as white. The magenta surface adds an interesting, quite organic, expression to the structure, almost like enlarged butterfly wings.’ (Author’s observation log: Observation indoor, set-up A, 29-10-2010, 3:50pm, sunny sky condition, sample Th.ch-T7)

This feature created an additional type of low-technology based colour changing effect on the fabric within the viewed space, compared to the effect created by the thermochromic dyes. The effect was visible regardless of sky conditions, but rather dependent on where within the room the viewer was located (CD-ROM, Film 1, and Figures 4.17-4.20 visualises the effect). This colour change may potentially be used for creating dynamic effects within a space, either in conjunction with the effect created by the thermochromic dyes or as an effect in its own right.

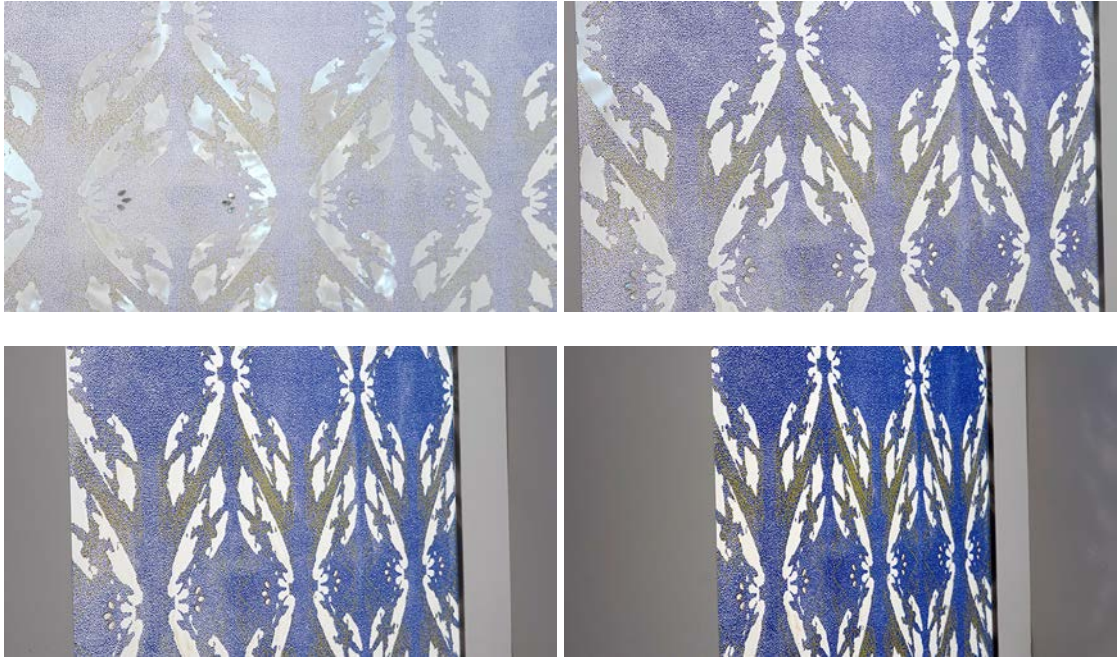


Figure 4.17-4.20 Stills from Film 1, on the CD-ROM, visualising the change in chromaticness within the silk-viscose velvet sample depending on viewing angle. (Photography: Film & Bildstudion AB)



Figure 4.21 Selection of the pile substrates tested.

The other printed heavy materials tested, see Figure 4.21, did not provide this behaviour, some not at all but the velour and the cotton loosely showed the aesthetic effect. However, it was still notably less than in the silk-viscose velvet. The aesthetic effect within the silk-viscose velvet appeared to be due to the decreased density of the construction of the material, combined with the softness and length of the pile of the material. This combination of materials and construction was only found in the silk-viscose velvet of the pile fabric structures tested. The added effects found in the silk-

viscose velvet were considered to fit well with the overall expression and the inspiration taken from ‘butterflies’. The effect was interesting since this thesis has a colour change emphasis, as well as from an aesthetic point of view. The silk-viscose velvet was therefore chosen for further investigations.

The following white substrate fabrics of different thicknesses were selected for further investigation: see-through silk chiffon, semi heavy polyester-viscose, acetate satin and silk-viscose satin, as well as heavy silk-viscose satin.

4.3 The behaviour of printed thermochromic dyes when activated by sunlight

This section presents a selection of the data collected during the experimental work of this chapter. The data presented (excerpts from the observation log and photographs) are selected to illustrate and support the results presented in sections 4.4 and 4.5. Samples of the selected materials, silk chiffon (s.ch), polyester-viscose (p-v), silk-viscose satin (s-v.s) and silk-viscose velvet (s-v.v) were printed using the pre-set colour palette, yellow (Y), orange (O), magenta (M), light purple (LP), dark purple (DP), light blue (LB), dark blue (DB), blue-green (BG) and mint-green (MG). Sunlight observations were carried out with monochromatic printed samples as well as samples printed with the pattern ‘butterfly ink’ using set-up A (indoor) as well as set-up B (outdoor), as explained in section 3.7.2 and Graphics 4.1-4.2. 40% of approximately 55 observed samples were printed using only leuco dyes (TLD), while the other 60% were printed in combination with permanent pigments (TLD + PP) (see Table 4.3).

Table 4.3 Selection of printed samples used during observations of the relationship between sky conditions and the colour change of the thermochromic dyes.

Dye/Pigments	Colour	Activation temp (AT)	Substrate fabric
TLD	(Y)	20°C	p-v
TLD	(O)	22°C	p-v
TLD	(M)	27°C, 31°C and 47°C	s.ch, p-v, s-v.s and s-v.v
TLD	(M)	27°C, 31°C and 47°C	s.ch, p-v, s-v.s and s-v.v
TLD + PP	(LP)	27°C, 31°C and 47°C	s.ch, p-v, s-v.s and s-v.v
TLD + PP	(DP)	27°C, 31°C and 47°C	s.ch, p-v, s-v.s and s-v.v
TLD + PP	(BG)	27°C,	s.ch, p-v, s-v.s and s-v.v
TLD + PP	(MG)	27°C	s.ch, p-v, s-v.s and s-v.v
TLD + PP*	(M, LP, O)	27°C and 31°C	p-v, s-v.s and s-v.v
TLD + PP*	(M, BG, O)	27°C	p-v, s-v.s and s-v.v

* Printed with the ‘butterfly pattern’, the documented AT is printed within one and the same sample, on the three respective substrates.

The indoor observations were repeated four times over the year, but focused on the summer months. The main observations with the outdoor set-up were carried out during the summer months, to provide the temperatures necessary to cause colour change (for temperature curves, see Appendix D). The observations were conducted to establish the behaviour of the colour change of the thermochromic dyes when activated in sunlight, see examples in Figures 4.22-4.28. The thermochromic dyes are programmed to change colour at or above their activation temperature. (LCR Hallcrest, n.d.; Matsui, n.d.) Observations of the samples printed with thermochromic dyes demonstrated that the behaviour in terms of the dynamic colour change depended on their placement (free-hanging or towards a contact surface). The observations further demonstrated that the colour change was closely linked to the level of sunlight (the amount of solar irradiation), the sky conditions (sunny or cloudy sky) as well as the ambient temperature.

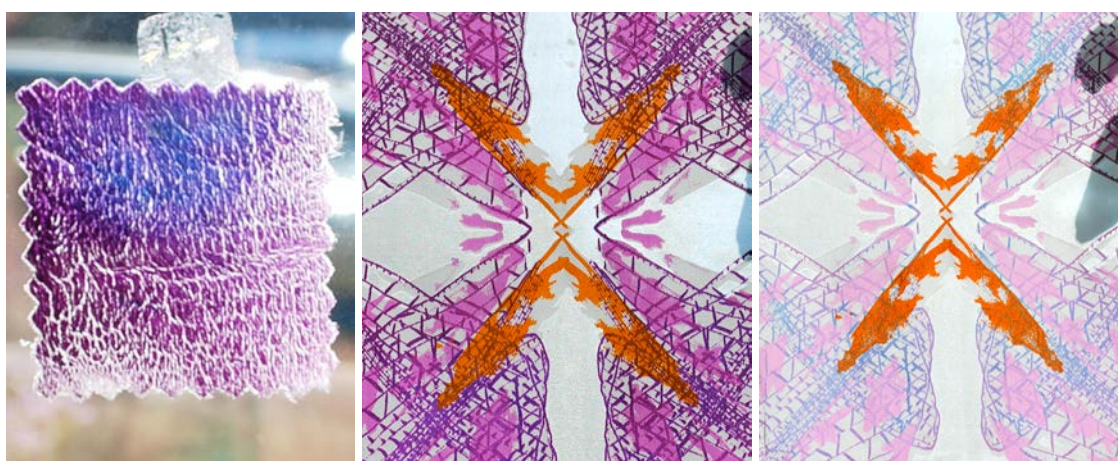


Figure 4.22 (left) Silk-viscose velvet sample printed in dark purple with AT 27°C, observed during indoor observations in sunny sky conditions. The sample has started to colour change due to the heat from the sunlight. Figures 4.23-4.24 (centre and left) Sample printed with the thermochromic colours light purple AT 27°C and magenta AT 31°C as well as the orange permanent pigment. Observed indoors during sunny sky, before (4.23) and after (4.24) activation. The light purple has moved towards blue and the dark magenta towards a light magenta colour, the orange is unchanged.

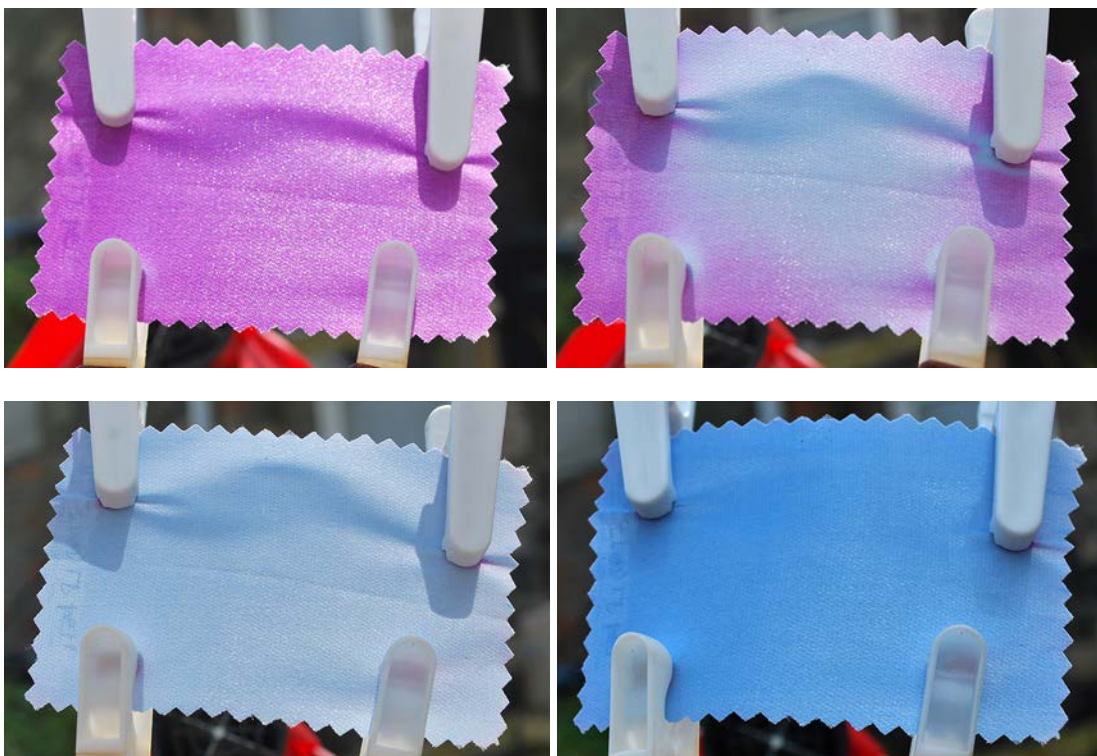


Figure 4.25 (top left) Magenta printed sample, AT 27°C, during outdoor observations, after the sky conditions has changed from cloudy sky to sunny sky, before samples have been activated. The sample provides an interesting glittering, sparkling effect in the sunlight. Figure 4.26 (top right) Same sample during activation through sunlight. Figure 4.27 (low left) The sample is fully activated, due to the sunlight. Figure 4.28 (low right) Same sample in cloudy sky conditions. The glittering, sparkling effect observed in the sample during sunny sky conditions has disappeared and the sample, additionally, appears to be duller and darker in the colour outcome.

Table 4.4 Excerpts from the observation log of how the samples printed with leuco dyes behaved when the colour change was activated through sunlight.

Date/Time	Weather	Viewing distance	Comment (regarding the different samples #)
Indoor Set-up A 07-08-2012 4.50pm	Sunny sky	0.5-1.5m	Th.ch-T74 (s-v.s): Sample printed with thermochromic dye, with an activation temperature of 27°C. The dark purple sample provided a colour change towards blue, even though the sunny sky had lower amounts of cloud coverage.
20-06-2011 4.40-5.00pm	Sunny sky		The colour change within the sample appeared to start to fade (before the whole surface had changed), and the sample appeared to reverse to an inactive state, as the sunlight went behind a cloud. The colour change reverted back to an active state a while after the cloud had passed the sun.
20-06-2011 4.40pm	Cloudy sky		No colour change within the sample. It appeared as if there was not enough sunlight to activate the sample.
Outdoor Set-up B	Sunny sky		The sample did not reach a colour change when hanging in direct sunlight, free-mounted with a tripod. The

10-08-2012 3.16pm 4.19pm	Sunny sky		shaded ambient temperature was around 22°C. The sample was activated when placed in direct sunlight on a white solid background. The sample provided a change over the whole surface. The shaded ambient temperature was still around 22°C.
Indoor Set-up A 07-08-2012 4.55pm	Sunny sky	0.5-1.5m	Th.ch-T180 (s-v.v): Sample printed with thermochromic dye, with an activation temperature of 31°C. The magenta sample provided a colour change towards a light magenta approaching the white colour of the substrate, when the sunlight had reached a position in the sky so the sunlight hit the sample. An all over colour change was noticed after approximately 45min.
Outdoor Set-up B 09-08-2012 3.35pm	Sunny sky		The magenta sample did not reach a colour change when hanging in direct sunlight, free-mounted on the tripod. The ambient temperature in the shade light was around 22°C.
Indoor Set-up A 04-06-2011 4.48pm	Sunny sky	0.5-1.5m	Th.ch-T105 (p-v): Sample printed with thermochromic dye, with an activation temperature of 22°C. The orange sample provided a prolonged colour change towards a light orange approaching the white colour of the substrate, as ambient temperature reached the activation temperature of the thermochromic dye. The ambient temperature of the room was around 22°C.
Outdoor Set-up B 08-08-2012 10.10am	Sunny sky		The orange sample provided a colour change towards a light orange approaching the white colour of the substrate, when the sunlight reached a position in the sky so the sunlight hit the sample. An all over colour change was noticed within minutes as the sunlight hit the sample.
10.15am	In shade		The sample reversed the activation, to certain extent, to a darker orange when placed in shade. The shaded ambient temperature was around 22°C.
Indoor Set-up A 04-06-2011 4.37pm	Sunny sky	0.5-1.5m	Th.ch-T106 (p-v): Sample printed with thermochromic dye, with an activation temperature of 20°C. The yellow sample provided a prolonged colour change towards the white colour of the substrate, due to the ambient temperature reaching the activation temperature of the thermochromic dye. The ambient temperature of the room was around 22°C.
Outdoor Set-up B 08-08-2012 10.05am	Sunny sky		The yellow sample had a prolonged colour change towards the white colour of the substrate, within the outdoor scenario, regardless of whether the sample was placed in the direct sunlight or shade. The shaded ambient temperature was around 22°C.
Indoor Set-up A 28-08-2012 4.59pm	Sunny sky	0.5-1.5m	<i>Th.ch-T76 (s-v.v): Sample printed with thermochromic dyes, with an activation temperature of 27°C. The sample was placed so half of the sample was in direct sunlight and half was in shade. The sunlit part provided a colour change from dark purple to blue, whereas the part in shade remained inactivated (dark purple).</i>
Indoor Set-up A 26-02-2013 12.05pm	Sunny sky	0.5-1.5m	Th.ch-T101 (s-v.s): Sample printed with thermochromic dye, with an activation temperature of 31°C. The magenta sample provided a colour change towards light pink approaching the white colour of the substrate, as the sunlight reached a position in the sky so that the sunlight

Outdoor Set-up B 26-02-2013 12.20pm	Sunny sky		hit the sample. The magenta sample did not change within the outdoor scenario, regardless of whether the sample was placed in the direct sunlight or shade. The ambient temperature was around 9°C.
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The observed samples behaved slightly differently when mounted close to the windowpane indoors, as in set-up A (see Figure 3.11), compared to when they were hung freely on a tripod outdoors, as in set-up B (see Figure 3.12). A common feature for both activation scenarios was that the printed samples, with an activation temperature that was set below the ambient temperature of the air, acquired a prolonged active state (state 2) as long as the ambient temperature remained constant.

4.3.1 *Thermochromic dyes with an activation temperature lower than or equal to the ambient temperature*

An analysis was conducted on the basis of the group of observations of samples that utilise thermochromic dyes with an activation temperature *lower or equal* to the ambient temperature. The data were analysed, as illustrated in Graphic 4.3, to detect patterns of behaviour within the colour change of the thermochromic dye in either sunny or cloudy sky conditions. The variables that were studied were: substrate thickness, colour of the dyes and activation temperatures. Samples were observed indoors, during sunny and cloudy conditions, as well as outdoors, also during both sunny and cloudy conditions. The activation temperatures of the 20°C as well as the 22°C dyes reached a prolonged active state (state 2) in the indoor set-up, due to an ambient room temperature of around 22°C. For an example of this, see the orange printed sample Th.ch-T106, observation indoors on 4th June 2011, at 4.48pm in Table 4.4 as well as in Figures 4.29-4.30. The 22°C sample acquired a prolonged intermediate active state when the room temperature was around 20°C. The colour of the thermochromic dye was in an intermediate state (between states 1 and 2). The 20°C sample remained in a prolonged active state during the outdoor summer observation when the air was at an ambient temperature above 20°C. For examples of this effect, see yellow printed sample Th.ch-T106, outdoor observations on 8th August 2012, at 10.05am in Table 4.4 as well as in Figures 4.31-4.32.



Figure 4.29 (left) Inactive polyester-viscose sample, Th.ch-T105, printed with thermochromic orange, AT 22°C. Figure 4.30 (right) Same sample semi-activated regardless of sky conditions, due to the ambient temperature of 20°C within the room.

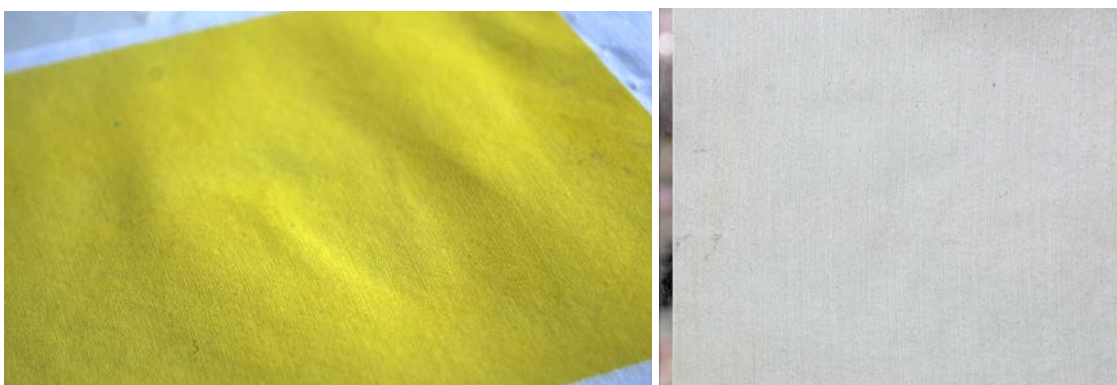


Figure 4.31 (left) Inactive polyester-viscose sample, Th.ch-T106, printed with thermochromic yellow, AT 20°C. Figure 4.32 (right) Same sample activated regardless of sky conditions, due to an ambient temperature outdoors above 20°C.

The prolonged active state was observed regardless of sky conditions or if the sample was placed in shade or in sunlight. In these cases, the colour change was triggered by the ambient temperature rather than by the solar irradiation. A colour change activated in set-up B proved to be more dependent on the ambient temperature in the air, influenced by geographical location as well as the time of day, rather than the presence of the sunlight. In the outdoor set-up, ambient air temperatures were generally not reached for samples printed with thermochromic dyes with activation temperatures of 27°C, 31°C or 47°C. The average outdoor temperature within the areas in which the observations were carried out (Scottish Borders, UK and Scania region, Sweden) for June, July and August was below 27°C. The Scottish Borders has an average ambient summer temperature at 13-15°C with average maximum temperatures in the range 17-18°C. The Scania region has an average ambient summer temperature in the range 16-18°C, with average maximum temperatures in the range 19-22°C. For temperature curves and more detailed

information regarding the temperature statistics see Appendix D. However, it is reasonable to predict that temperatures in the range 27°C-31°C would occur every once in a while during the summer months in these locations, but not on a general basis. These higher activation temperatures would, however, be attained more frequently over the summer months in locations further south (closer to the equator), for example in Seville, Spain. Seville has an average ambient summer temperature of 25-28°C with average maximum temperatures of 32-36°C (see Appendix D).

If a more prolonged colour change is desired during the day, the textile printmaker practitioner would be recommended to choose a leuco dye with an activation temperature around the average outdoor temperature taking into account when and where the outdoor sun-screening application will be used. Indoor applications using dyes with an activation temperature below average ambient temperature would need to be located in a position where the indoor room temperature would fluctuate over several degrees to provide the colour changing effects.

4.3.2 *Thermochromic dyes with an activation temperature higher than the ambient temperature in sunny sky conditions*

An analysis was conducted on the basis of the group of observations of samples using dyes that have activation temperatures (AT) *higher* than the ambient temperature and that were carried out during sunny sky conditions. The data were analysed to detect patterns of behaviour within the colour change of the thermochromic dye, as illustrated in Graphic 4.3 (with the exception that this study was only carried out in sunny sky conditions). The variables that were studied in sunny sky conditions, both indoor as well as outdoor, were: substrate thickness, colour of the dyes and activation temperatures.

The colour change became more dependent on the presence of the sunlight when the ambient temperature of the air was below the activation temperature of the thermochromic dye. The observed samples remained, or reverted to, an inactive state if placed in shade or in intermediate shade. For an example of this, see sample Th.ch-T74, indoor observation on 20th June 2011, at 4.40pm in Table 4.4. Observations of printed samples that were mounted half in the sunlight and half in the shade only showed a colour change in the part of the sample that was exposed to the sunlight. The silk-viscose sample Th.ch-T76 (indoor observation, August, 28, 2012, 4.59pm) in Table 4.4 and the polyester-viscose sample in Figure 4.33, are good examples of this.



Figure 4.33 Polyester-viscose sample half colour changed in sunlight and half inactivated in shade.

The observations of printed thermochromic dye samples with activation temperatures below the ambient temperature using set-up A (indoors) demonstrated that the colour change was in part dependent on the ability of the sunlight to sufficiently heat up the windowpane, which was in contact with the printed sample. The windowpane is normally a couple of degrees warmer in the centre of the glass compared to the edges. The temperature of the windowpane increases when the sun is shining on it (Energimyndigheten, n.d., p.3). The heating of textiles printed with thermochromic dyes is also partly related to the solar transmission (the amount of heat from the sun that is transmitted through the window). Some solar energy that is incident on the windowpane is reflected outside and some is absorbed and then re-emitted through the windowpane to heat the textile and the inside of the building. The solar transmittance added to the absorbed part that is re-emitted inside equals the ‘total solar energy transmittance’ (TSET) or ‘solar heat gain coefficient’ (SHGC). The TSET helps to explain the heating effect that the sunlight has on the printed textile. (Karlsson, 2001, p.14) The surface temperature required for activation by the windowpane will vary depending on amount of solar radiation transmitted. A windowpane with standard double glazing (as used in the tests described within this thesis) has a solar transmission percentage of 76% while a windowpane with standard triple glazing has a solar transmission percentage of 68%. (Energimyndigheten, n.d., p.4) The amount of heat transferred through to the inner surface of the window glazing (the thermal conductivity of the window) can be calculated using the ‘internal heat coefficient’ (h_i). The h_i value is calculated using the level of the emittance of the inner surface of the glazing (relating to the insulation properties of the glass), the level of convection inside the window (the transfer of energy from one point to another by the movement of medium, i.e. air) and the level of thermal radiation (the exchange of radiation between surfaces and surroundings). (Karlsson, 2001, p.5) The h_i

value provides a means for the textile printmaker practitioner to obtain information regarding surface temperatures for a specific type of window solution (both type of glazing as well as type of frame), to assist selection of the activation temperatures of dyes that would be suitable for the intended application.

During observations, the sun was required to provide a temperature of the contact surface that was close to the chosen activation temperature of the thermochromic dyes that were used in order to provide a colour change. Experiments showed that a temperature of approximately 30°C could be reached with the set-up and geographical location used, even during autumn and winter months (see Table 4.5). The sample was mounted in the centre of the windowpane (set-up A). The tests were carried out during sunny sky conditions (lux value: 67,000), on a silk-viscose sample printed with dark purple with activation temperature at 27°C.

Table 4.5 Examples of temperature curves of the windowpane and the textile printed with leuco dyes, measured during the autumn and winter months

Date/Time	1 cm from windowpane	Windowpane	DP printed sample	Comments
03-09-2012 3:20pm	23.6°C	25.1°C	26.1°C	Sunlight reaches the window
3:55pm	25°C	26.3°C	28.1°C	Colour change starts to appear
4:30pm	27.0°C	27.4°C	29.3°C	The sample is fully colour changed
27-02-2013 10:32am	20.6°C	19.6°C	20.2°C	Sunlight reaches the window
11:00am	23.2°C	25.4°C	26.6-7°C	Colour change starts to appear
11:35am	27.4°C	29.6°C	29.9-30.0°C	The sample is fully colour changed

The quantitative measurements of the temperature of the windowpane and the mounted samples printed with thermochromic dyes, conducted with a hand held Eirelec E 5000 thermometer probe, demonstrated a relationship between the profile of temperature rise within the glass and the colour change within the samples (see examples in Table 4.5). The ambient temperatures of the air within the rooms at the time of the measurements were around 20-22°C. When in direct sunlight the air temperature close to the window, approximately 1cm from the glass, was 4 to 5°C higher than the temperature in the room. The measurements varied depending on the season and time of day. The temperature at the surface of the windowpane generally was approximately 1-3°C higher still compared to the ambient room temperature, during

sunny sky condition. The temperature increase within the printed textile samples to a certain extent followed the temperature rise of the surface of the windowpane facing inwards. The temperature of the printed samples showed a smaller increase of approximately 1-2°C compared to the temperature of the windowpane.

Quantitative measurements were additionally carried out during sunny sky conditions (lux value: 67,000) using silk-viscose satin samples printed with three different colours (orange, magenta and dark-purple) as well as four different activation temperatures (22°C, 27°C, 31°C and 47°C) (see example in Table 4.6) The experiments provided a colour change within fabric samples printed with dyes with activation temperatures of 22°C, 27°C and 31°C, but not the 47°C sample.

Table 4.6 Measurement of the increase of the temperatures of the windowpane and the textile sample printed with leuco dyes.

Date/Time	Window	O 22°C	DP 27°C	M 31°C	M 47°C	Comments
27-02-2013 10:32am	19.6°C	20.0°C	20.2°C	20.2°C	20.2°C	The sunlight reaches the window.
10:34am		20.2°C				Half the samples are in sunlight, half the O samples have changed colour.
10:39am		20.7°C				The samples are fully in sunlight; the O sample has changed to a light orange tint all over. The others are unchanged.
10:52am	24.2°C	24.1°C	24.8°C	24.8°C	24.8°C	O sample is virtually white all over.
11:00am	25.4°C		26.6- 26.7°C	25.8°C		Colour change starts to appear in DP27 and M31. A slightly bluer purple and a slightly lighter magenta have appeared in the centre of the samples. The darker sample reaches a higher temperature faster compared to the lighter sample.
11:13	27.0°C		28.2°C	27.5°C		The DP27 and M31 have achieved an area of clear blue, as well as light magenta, approaching white in the centre of the samples. Only edges are unchanged.
11:35am	29.6°C		29.9- 30.0°C	29.9- 30.0°C	29.9- 30.0°C	The DP27 and M31 are fully activated. M47 never changed.

The colour change of the samples printed with dyes with reported activation temperatures of 27°C and 31°C started before the windowpane facing inwards had reached either of these two temperatures. The time it took for the different printed samples to reach an all-over colour change differed depending on the relationship

between the activation temperature and the ‘internal heat coefficient’ (h_i) of the surface of the windowpane, which determines the temperature of the contact surface of the printed samples. The time for colour change to take place was also dependent on the ambient air environment around the textile, which is affected by ‘the total solar energy transmittance’ (TSET). The samples printed with dyes with a lower activation temperature, AT closer to the surface temperature of the windowpane, such as the 22°C samples, predictably registered a notably shorter time to change colour, compared to those with higher activation temperatures. However, repeatedly during tests, the 27°C sample did *not* change notably faster compared to the 31°C sample. Instead, the dyes with these two separate activation temperatures displayed a complete activation after approximately the same time. Nevertheless, the purple 27°C sample did appear to change slightly faster than the magenta 31°C sample (see examples in Table 4.6). The experiments resulted in the experience of a larger time frame from start to complete activation between the samples printed with activation temperature of 22°C and 27°C compared to the AT 27°C and AT 31°C samples, even though the difference in activation temperatures between both 22°C and 27°C as well as between 27°C and 31°C is similar, around 5°C. The quantitative measurement of the temperature curves of the printed samples, in Table 4.6, indicates that the rate of colour change probably is not only due to the activation temperature, but also to the choice of lightness of hue of the printed sample. The temperature curve of the printed darker purple sample was faster compared to the magenta and the orange samples, i.e. it took less time to move from the start temperature to the final temperature. The dark purple sample measured a temperature of roughly 1-1.5°C higher after 30 minutes exposure in sunlight, compared to the two lighter colours (see Table 4.6). This is considered to be due to the lower albedo⁵ of the dark purple colour, compared to the lighter colours.

The precision of the definitions regarding the stages of the colour change presents difficulties. The times at the start of a colour change and for complete all-over colour change, for the observations described within this thesis, were based on a subjective decision that visual colour change had indeed taken place. The printed textiles remained in an inactive state when the activation temperature of the dye was much

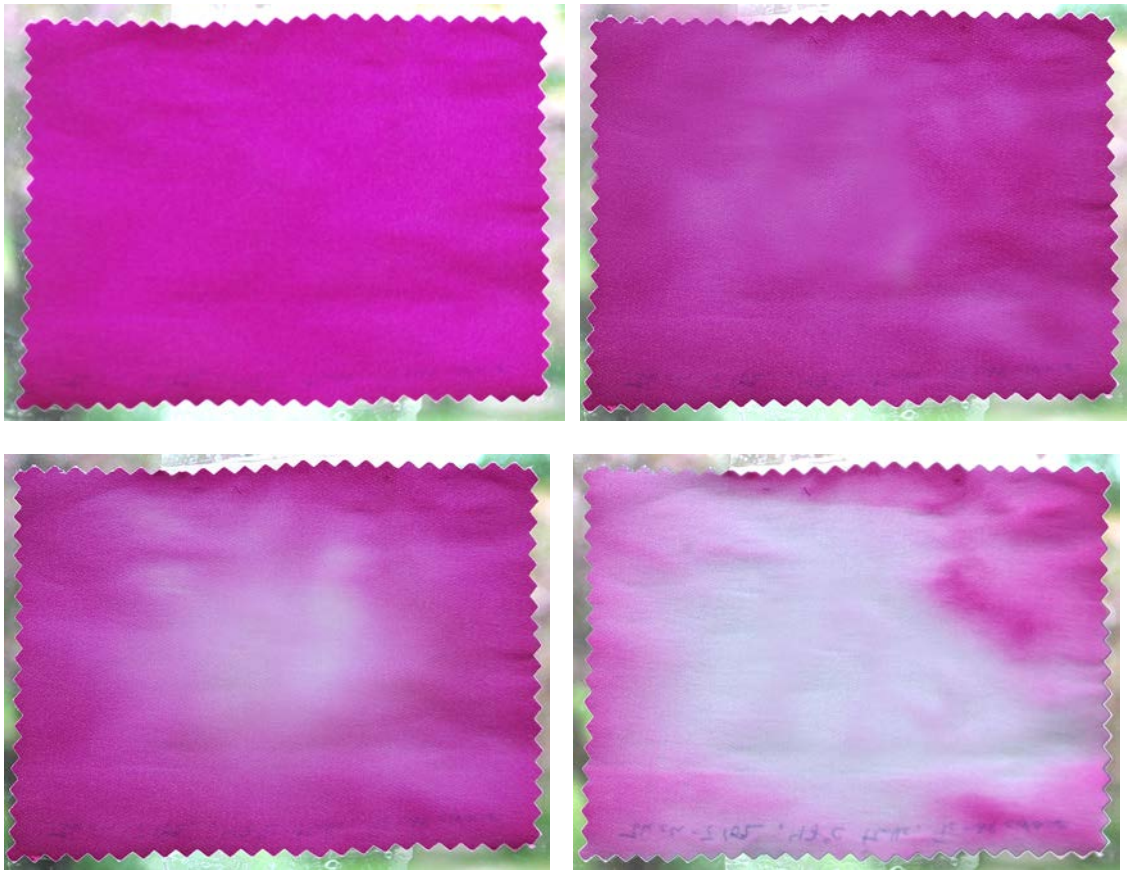
⁵ Albedo is the value of the reflection of light for an object: an albedo near 1 is very bright and an albedo near 0 is very dark. (Spellman and Bieber, 2012, p.420)

higher than either the ambient room temperature or the surface temperature of the windowpane, such as for the 47°C dye in Table 4.6. A complete colour change could take times ranging from more than one hour to only minutes. The time for the change was taken from the moment the textile samples printed with thermochromic dyes started to change colour, until the printed surface had resulted in a more or less complete colour change. In some cases, this would be approximately the same timeframe as from when the sunlight first illuminated the mounted printed samples until the printed surface had resulted in a more or less complete colour change. An example of this is for dyes with activation temperature of 22°C (see Table 4.7). However, in some tests there was a much larger difference between the time when direct sunlight first illuminated the sample until the time of the colour change, such as for observations of the dyes with activation temperatures of 27°C and 31°C (see Table 4.7).

Table 4.7 Approximate times for colour change, tests carried out 2013-02-27, during sunny sky condition

Time	O 22°C	DP 27°C	M 31°C	M 47°C	Comments
Time until initial colour change	1-2min	25min	25min	Remained inactive	The times are approximate due to the difficulties in visually observing the exact moment that the colour started to change. The time is set when the samples had received enough colour change to be visually observed.
Time until an complete colour change was reached	18min	1h	1h	Remained inactive	Both the DP27 and M31 reached an all over colour change within approx. 1h even though DP27 had a slightly lower activation temperature compared to M31.
Time from initial sunlight on samples until complete colour change	20min	1.5h	1.5h	Remained inactive	

The direction of the heat-spread through the sample appeared mainly to start in the centre of the printed samples and spread towards the edges of the fabric. All samples printed with an activation temperature of 22°C, 27°C and 31°C, more or less, clearly demonstrated this when indoors. The samples printed with thermochromic dyes were placed in direct sunlight. The heat-spread was slightly more difficult to monitor when it took place over a shorter timespan as in the case with the activation temperature of 22°C. The samples printed with dyes with activation temperatures of 27°C and the 31°C clearly demonstrated the direction of the heat-spread (see Figures 4.34-4.37).



Figures 4.34-4.37 Step-by-step pictures of thermochromic magenta printed sample, AT 27°C, demonstrating the spread of the colour change from the centre to the edges within the samples when observed in set-up A.

The heat-spread originated from a rather large focal point. The area expanded towards the edges until a clear all-over colour change was reached. As shown in Figures 4.36-4.37, the area between fully activated and inactivated dye created a smooth and soft light pink watercolour-like effect on the surface of the textile. This intermediate area in the colour change was defined as a ‘transitional colour zone’.

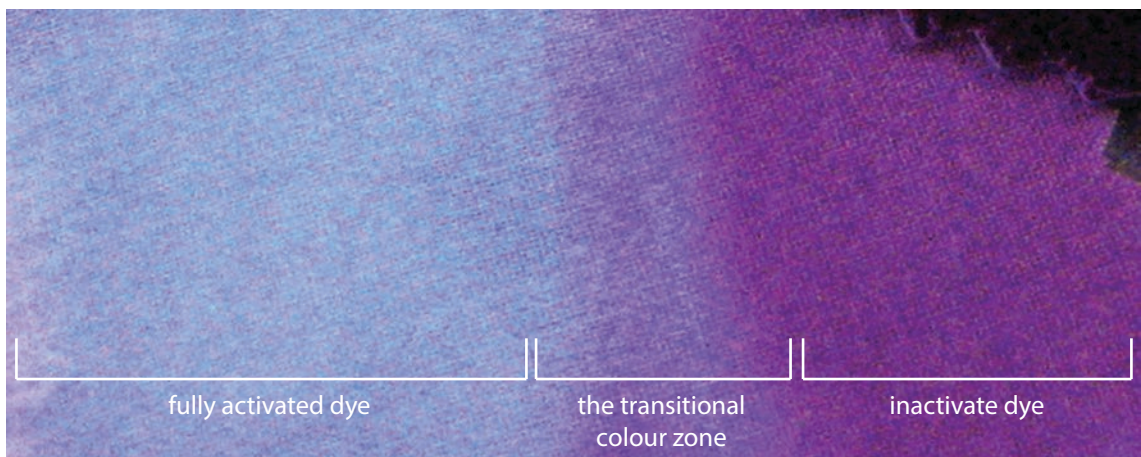


Figure 4.38 The transitional colour zone, the fully activated as well as inactive areas of the printed sample.

A further illustration of this feature for a different sample is given in Figure 4.38. The purple colour of the transitional colour zone of the sample in Figure 4.38, which changed colour towards blue, provided interestingly a blue-purple hue that was bluer and darker than the inactivated purple hue.

Outdoor observations where printed sample had been placed on either a light or dark surface provided colour change results similar to the indoor observations, set-up A. The surface acted as a solid contact surface for the printed samples, see Figure 4.39.

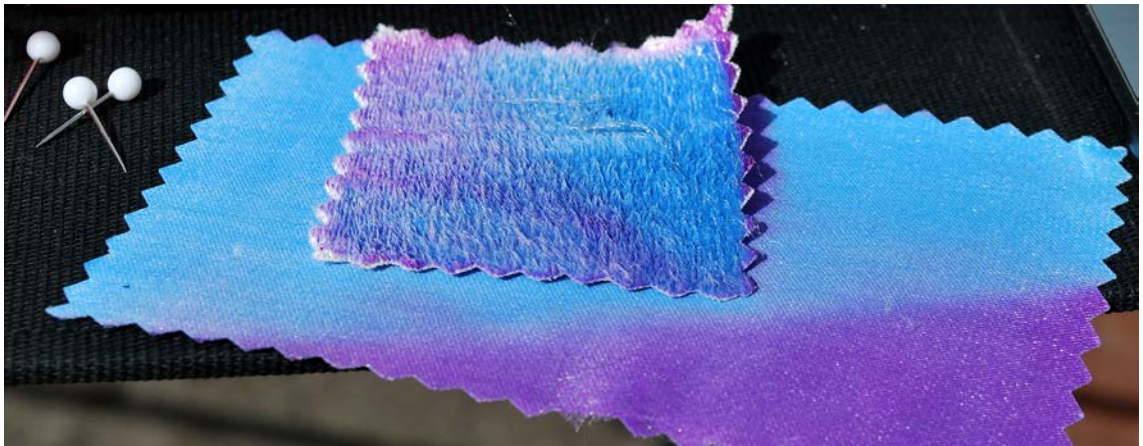


Figure 4.39 The part of the sample that is placed on the black, solid surface is activated (see blue areas of the sample), in contrast to the part that is free-hanging in the air, which is not activated and is purple.

This feature indicated that the conclusions from the indoor observations would also be applicable to an outdoor set-up where the samples printed with thermochromic dyes are mounted on a contact surface. However, the results from the outdoor tests differed markedly depending on the time of year, due to larger temperature differences in the summer compared to the winter months. The sunlight-activated samples printed with thermochromic dyes with activation temperatures of 22°C, 27°C and 31°C changed colour over the whole surface, when placed on the solid surface in the outdoor set-up during the sunny summer months, but not during winter months. Lower activation temperatures of the thermochromic dyes would be needed for use during the winter season. The printed substrate returned to the inactivated state when placed in shade in the summer observations. Darker surfaces, as the example in Figure 4.39, proved to be most efficient, as they have lower albedo compared to lighter colours. (Spellman and Bieber, 2012, p.420)

4.3.3 *Thermochromic dyes with an activation temperature higher than the ambient temperature observed during a sky containing clouds*

The analysis described in this section was conducted on the basis of the group of observations of samples that have activation temperatures *higher* than the ambient temperature. The data were analysed through the same framework as used to detect patterns of behaviour for the previous two groups of samples (see Graphic 4.3)

Some clouds were present during observations in conditions assessed both as sunny sky and as cloudy sky, the difference being the extent of cloud coverage. Sunny sky contained 0% up to approximately 15% sky coverage, whereas a cloudy sky consisted of approximately 25% to 80% sky coverage, as described in section 3.7.1. In general, the complete colour change, all over the printed surface, was only achieved in sunny sky conditions with either no clouds or a minimal amount (less than 15%) in the sky. Samples printed with thermochromic dyes with activation temperatures of 27°C and 31°C did not provide a colour change when observed in cloudy sky conditions, due to the lack of sunlight (see Table 4.8). This appeared mostly to be the case also when the sunlight provided measured lux values intermediate between sunny and cloudy sky conditions. However, more vague colour changes were reported on some occasions during lux values that were measured intermediate between sunny and cloudy sky conditions (see Table 4.8). The temperature measurements, in Table 4.8, of the polyester-viscose samples printed with leuco dyes, with activation temperatures of 27°C, 31°C and 47°C carried out on 05-03-2013, were measured when the clouds in the sky were both moving to cover and uncover the sun. The lux values were measured angled towards the sunlight.

Table 4.8 Measurement of the temperature on the printed samples as well as the lux values through the windowpane

Time	Lux x100	Window	LP 27°C	DP 31°C	LP 47°C	Comments*
10: 35am	337-340	19.3°C	19.4°C	19.5°C	19.4°C	The sunlight reaches the window, some clouds in the sky. (C)
11:06am		22.8°C	22.6°C	23.0°C	23.0°C	No colour change. (C)
11:23am	120-145					More clouds covering the sun. (C)
10:35am	380-410	20.8°C	21.4°C	21.4°C	21.4°C	The bigger clouds have moved away from the sun. (BCS)
11:43:am	550					Stronger sunlight, less clouds. (BCS)
11:55am				25.0°C		Small colour change towards blue in some parts of sample DP31, where there is air between sample and

						window (air measures 27.4°C). (BCS)
12:30pm	380-400			23.5°C		Less sun. The colour in DP31 has gone back to an inactive state. (BCS)
1:38:pm	550					Stronger sunlight, less clouds. (BCS)
1:41pm		23.9°C		24.5°C		Small colour change towards blue in some parts of sample DP31, where there is air between sample and window (air measures 27.4°C). The LP27 and LP47 never colour changed. (BCS)

* C = Lux value of a cloudy sky conditions, BCS = Lux value between sunny and cloudy sky conditions

However, the observed samples printed with dyes with activation temperatures of 27°C and 31°C did on some occasions provide a partial colour change during conditions with a sky containing some clouds. However, this occurred mainly during observations when the cloud coverage was within the limits for sunny sky conditions (see example set-up A, Th.ch-T74, 07-08-2012, 4.50pm, Table 4.3). Several results from the indoor observations (set-up A) during a sunny sky with clouds indicated that the timeframe for which the colour change remained activated was closely related the size of any moving clouds and their speed of movement. This was especially the case with smaller, white, clouds that moved quickly across the sky, which reduced the time when sunlight was restricted. The colour change in samples printed with thermochromic dyes with an activation temperature of 27°C and 31°C, under these conditions, provided a colour change that oscillated back and forth between an active and inactive state. Similar colour change behaviour as for a sunny sky with some cloud coverage using set-up A (indoor) were also observed in the outdoor set-up. This was observed during sunny sky conditions with some cloud coverage, when the printed textiles were placed on a solid surface as the ground (see Figure 4.39). The 27°C and 31°C samples provided colour change when placed in direct sunlight at an ambient temperature of around 22°C.

4.4 Design variables when using sunlight as a direct activator for printed thermochromic dyes

This section presents a discussion of the definition of a set of design variables, and also proposed amendments to the dynamic descriptors that relate to thermochromic dyes, which are activated through direct solar activation. The indoor and outdoor observations, using set-ups A and B, that are presented and discussed in chapter 4.3, resulted, through analyses, in the definitions of the following six design variables; ‘amount of sunlight’, ‘time interval’, ‘temporal pattern’, ‘contact surfaces’, ‘ambient

temperature’ and ‘distribution of sunlight’. An understanding of the effected design variables may be used to provide a tool for textile printmaker practitioners when designing textile sun-screening applications that incorporate printed thermochromic dyes that use the sunlight as an activator. Some of the statements and conclusions presented in this section may appear obvious, but they need to be stated in the context of the research topic.

4.4.1 *Design variable: Amount of sunlight*

The design variable ‘amount of sunlight’ refers to the levels of thermal energy produced by sunlight that are needed to create an intended colour change within a textile application. In such a situation, the weather conditions are therefore key to providing enough heat to activate the thermochromic dyes. The designer needs to consider the effects in changeability that can be created due to placement of the textile, as well as the impact of an indoor compared to an outdoor set-up. Indoor observations indicated that the all-over colour changed surfaces were determined largely by the sunlight’s ability to raise the temperature of both the textile and the contact surface in order to reach the activation temperature of the dyes within the printed fabric. Samples exhibited all-over colour changes predominantly in sunny sky conditions. In order to provide obvious dynamic reversibility, i.e. rapid colour changes, the textiles needed to be printed using thermochromic dyes holding activation temperatures slightly above the ambient temperature of the environment. Samples with a lower activation temperature, compared to the ambient air temperature, provided a prolonged colour-changed state. In an outdoor set-up, the colour change was largely dependent on both the amount of accessible sunlight as well as the, often fluctuating, ambient temperatures.

4.4.2 *Design variable: Time interval*

The definition of the design variable ‘time interval’ proposed in this section is applicable to a wider context in a more general discussion of dynamic colour change and not only to sunlight activated applications using thermochromic materials. However, the author has chosen to present a discussion of the meaning of the terminology here in section 4.4, rather than 4.5, in the interest of clarity for the reader. Worbin’s previously-defined design variable ‘time’, see section 2.2.1, has a focus on the activator of the dynamic material, discussing the length of time that an activator is active as well as inactive, for example the ‘time that the textile is exposed to heat’.

(Worbin, 2010, p.264) In contrast, the design variable ‘time interval’, as presented in this thesis, discusses *the time factors associated with the outcome of the dynamic effect* within the thermochromic material. This variable allows the designer to discuss not only the nature of actual dynamic effect, but also the speed of the colour change.

‘Time interval’ incorporates two separate definitions:

- (a) the approximate time it takes for the thermochromic dyes to undergo a colour change (t_1),
- (b) the approximate timespan during which the thermochromic dye stays either active or inactive (t_2), in each case as the sun comes and goes.

The definition of t_1 , see Figure 4.40, is the time taken for the thermochromic dye to change colour either from inactive (colour state 1) to active (colour state 2), identified as t_1^{i-a} , or vice versa (from colour state 2 to state 1), in which case it is identified as t_1^{a-i} . The t_1^{i-a} value of the colour change is measured as starting when the sample first shows a visual indication of a chromic effect and ending when the sample no longer continues to change colour (see Figure 4.40). The t_1^{a-i} value for the colour change is the inverse, i.e., the time from when the active state starts to reverse to an inactive state, until the sample no longer continues to change colour.

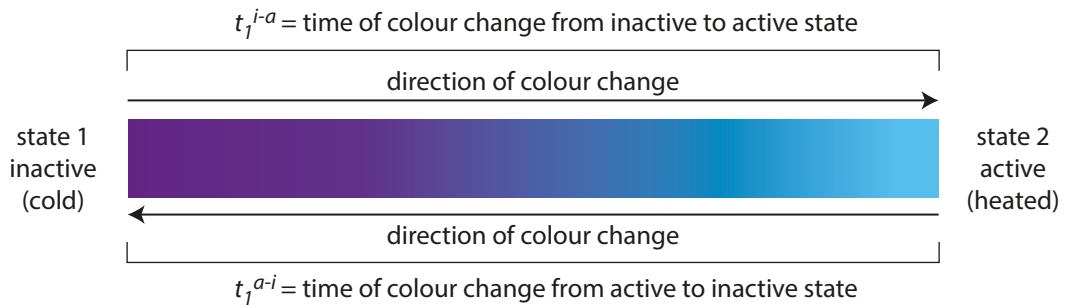


Figure 4.40 Visualisation of the definition of the design variable t_1 .

The definition of t_2 , see Figure 4.41, is the period of time that the thermochromic dyes stays either activated (t_2^a) or inactivated (t_2^i). The active state (t_2^a) (see the blue area in the lower rectangle in Figure 4.41) starts when the chromic effect no longer appears to change because the dye has obtained either a complete or a partial colour change, and ends when a reverse colour change, from an active colour state to an inactive colour state, starts to take place. The time interval of the inactivated state (t_2^i) (see the purple area in the upper rectangular in Figure 4.41) is defined as the time from

when the chromic effect appears to have reversed to colour state 1 until the time when the chromic effect appears to have started once again to return towards state 2.

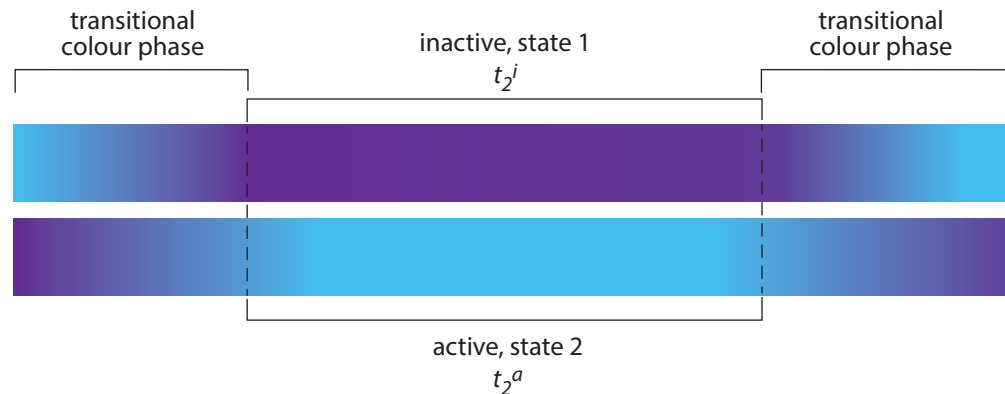


Figure 4.41 Visualisation of the definitions of the two t_2 design variables.

CD-ROM, Film 2 as well as Figures 4.42-4.47, visualise the chronological stages of the time intervals (t_1) and (t_2) of the colour changing process within a textile sun-screening application mounted on a windowpane, printed with a leuco dye with an activation temperature at 27°C.



Figure 4.42 (left) Time interval: the inactivated state (t_2^i). Figure 4.43 (right) Time interval: changing colour from inactive (purple) to active (blue) (t_1^{i-a}). (Photography: Film & Bildstudion AB)



Figure 4.44 (left) Same as Figure 4.43. Figure 4.45 (right) Time interval: the activated state (t_2^a). (Photography: Film & Bildstudion AB)



Figure 4.46 (left) Time interval: changing colour from active (blue) to inactive (purple) (t_l^{a-i}). Figure 4.47 (right) As Figure 4.42, time interval: the inactivated state (t_2^i). The sample has completed the cycle of the colour change of the thermochromic dye, inactive to active, then reversing to inactive. (Photography: Film & Bildstudion AB)

The time interval can, to a certain extent, be influenced in the design process through the choice of activation temperature of the thermochromic dyes. A lower activation temperature is, for example, likely to provide a shorter t_l as well as a longer t_2 , compared to a higher activation temperature. These measured times are necessarily approximate due to the properties of the thermochromic material, in that it does not proceed from inactive to active in the way that a switch alternates sharply between on and off, but rather in a more gradual way (see Figures 4.42-4.47). It generally takes a while until the colour change becomes perceptible visually. Therefore, the variable ‘time interval’ provides an estimate of the speed and duration of the colour change, i.e., either a fast or slow build up time or a colour change that persists for long or short intervals. The printed samples investigated when activated by sunlight, such as the examples in Table 4.6, that were able to achieve complete colour change covering the entire surface exhibited a range of timespans for colour change, from faster change with a t_l^{i-a} of approximately 20min, to slower colour changes with a t_l^{i-a} of over 1-1.5h. The time interval for the printed thermochromic dyes to change from colour state 1 to state 2 (t_l^{i-a}) as well as the time intervals during which the fabric provided a static active or inactive colour state (t_2), depended not only on the length of exposure to the sunlight allowing it to directly heat the textile, and lack of sunlight due to cloud coverage, but also the amount of heat that the sunlight produces at any contact surfaces, which was then transferred to the textile.

4.4.3 *Design variable: Temporal pattern*

As for the design variable ‘time interval’, previously presented, the definition of the design variable ‘temporal pattern’ is applicable to a wider context in a more general

discussion of dynamic colour change and not only to thermochromic textiles activated by the use of the sun. The author has chosen to present the definition of the terminology here in section 4.4 rather than 4.5, for the same reason as given in section 4.4.2. ‘Temporal pattern’ is defined, within this thesis, as *a continuous repetitive or random sequence of time intervals of colour change and inactive/active states*. The number of time intervals may vary from very few to infinitely many. Temporal patterns can be random or repetitive or a combination of both. Defining random temporal patterns in this way allows the discussion of types of activators, such as sunlight, which are, by nature, random. However, sunlight also exhibits a clearly defined repetitive temporal pattern, such as the hours of daylight as well as the cycle of the year.

The design variable ‘temporal pattern’, see Figure 4.48, is built up from a combination of the length of the time intervals between the inactive and the active colour states (t_1^{i-a} and t_1^{a-i}) as well as the length of the inactive and the active colour states (t_2^i and t_2^a). The ‘tempo’ of the temporal pattern may be fast or slow depending on the length of the individual time intervals.

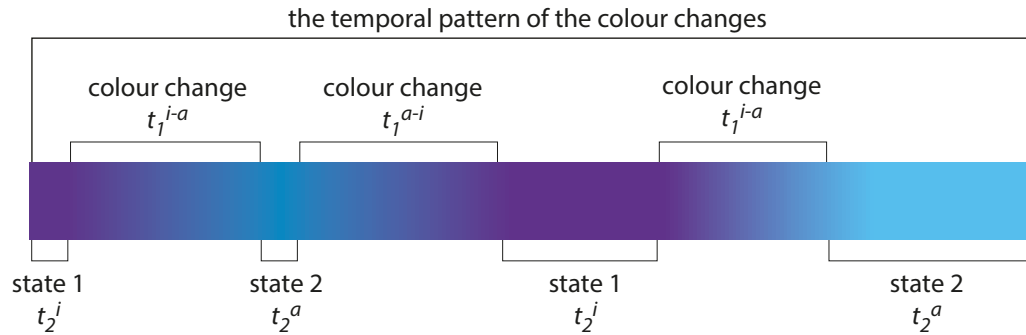
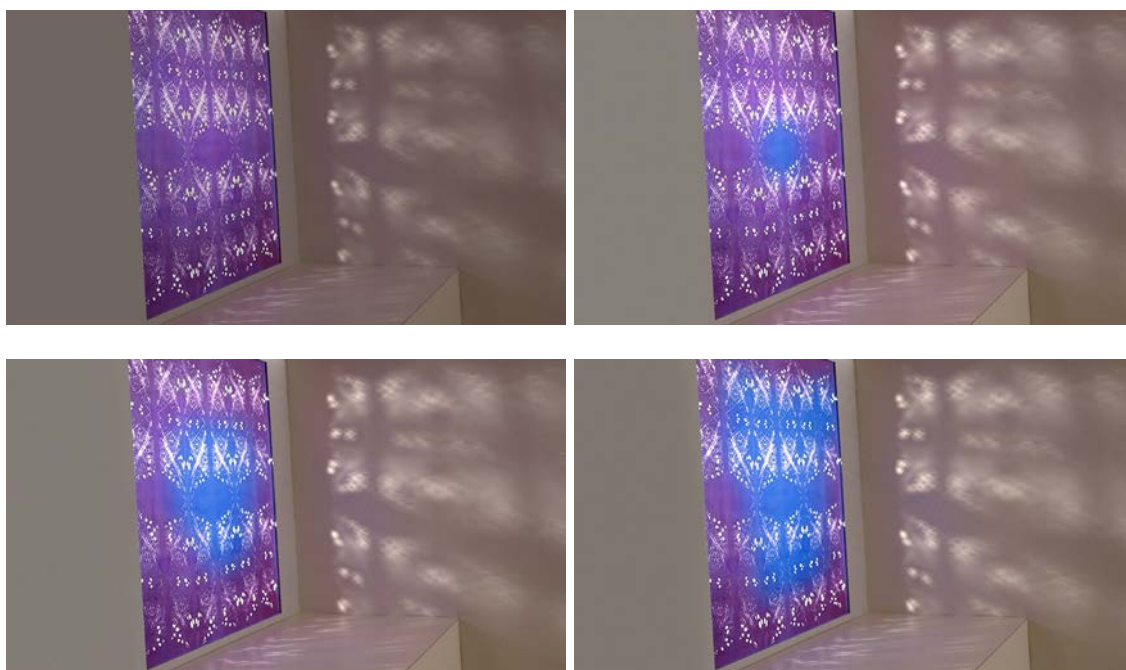


Figure 4.48 Visualisation of the definition of the relationship between the design variables ‘temporal pattern’ and ‘time interval’.

The designer needs to consider the effects that sunlight, within its role as an activator, will have on the colour change. The tempos and lengths of the individual sections of the temporal patterns are affected to a large extent by both the cycles of the day and the year, but it will also be affected to a lesser extent depending on the prevailing weather conditions. The rhythm of daylight will create a prolonged time interval of a dye in its inactive state, during the hours of the night-time and the possibility for activation during the sunlight hours of the day. The length of t_2^i and length of the possibility of t_2^a is, for obvious reasons, controlled by the times of sunset and sunrise and will therefore vary depending on the seasons and geographical location.

However, the temporal interval seen in the context of the weather conditions, provided the following observations in relation to tempo. A more constant sky created a slower tempo and alternating sky conditions led to a quicker tempo. Strong sunlight, with little or no cloud in the sky provided a slow temporal pattern, as did a cloudy day with very little sunlight. Sky conditions that altered between strong sunlight and fast moving clouds generally provided a slightly quicker temporal pattern. The design choice of activation temperature, as described in previous section, will also to some extent affect the temporal pattern of the chromic dyes. A lower activation temperature is, for example, likely to provide a slower temporal pattern, compared to a higher activation temperature.

CD-ROM, Film 3, part I as well as Figures 4.49-4.60, visualise the temporal pattern of the colour changing within a textile sun-screening application mounted on a windowpane, printed with a leuco dye with an activation temperature at 27°C.



Figures 4.49-4.52 The thermochromic dye changes from inactive (purple) to active (blue) as sunlight increases in strength, due to the sunny sky conditions. (Photography: Film & Bildstudion AB)

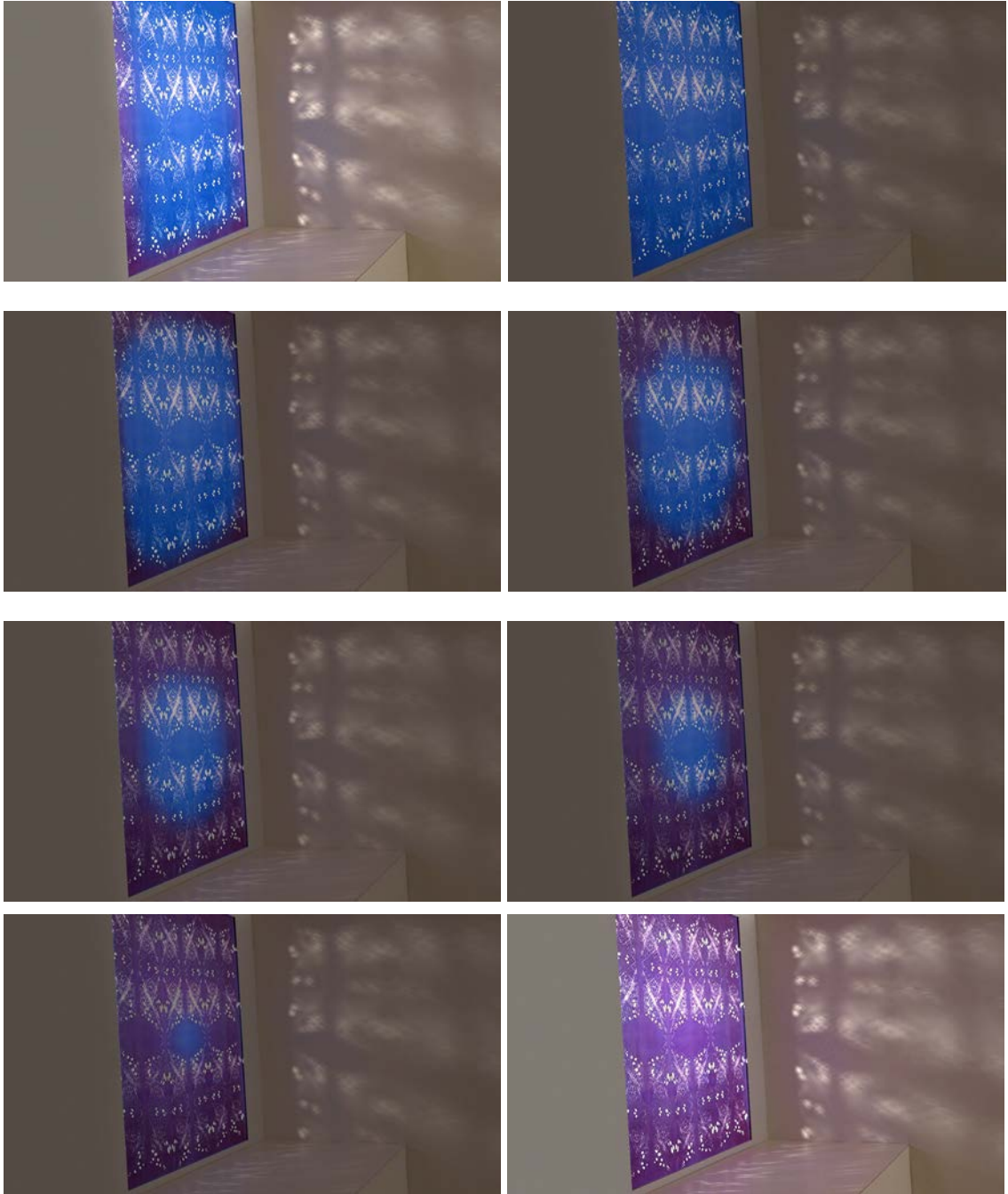


Figure 4.53 (upper left) The thermochromic dye changes from inactive (purple) to active (blue) as sunlight increases in strength, due to the sunny sky conditions. Figure 4.54 (upper right) The sunlight decreases in strength, due to cloudy sky conditions. Figure 4.55-4.59 (centre and lower left) The sample is reversing back to inactive (purple) from active (blue) as the sunlight decreases in strength, due to cloudy sky conditions. Figure 4.60 (lower right) The sunlight increases in strength, as the sky conditions revert from cloudy to sunny sky, which then initiates another colour changing cycle. (Photography: Film & Bildstudion AB)

4.4.4 *Design variable: The contact surface*

The design variable ‘contact surface’ defines the impact that a close touching surface has on the activation of the colour change of thermochromic dyes. Contact surfaces,

both in the indoor and the outdoor set-ups, facilitated the ability to activate the chromic dyes, as well as determining the speed of the colour change (t_I^{i-a} and t_I^{a-i}). Such effects were established through contact of the textile samples with the inner surface of the windowpane during observations in indoor set-up A. Surfaces and printed colours with low albedo (poor reflectors, good absorbers) resulted in slightly more efficient indirect heating of printed structures, compared to the surfaces with lower absorption values. During the design process the designer has to consider whether a contact surface will be present in the intended design application and, if so, how the contact surface will affect the time interval and spread of the colour change.

4.4.5 *Design variable: Ambient temperature*

The design variable ‘ambient temperature’, discusses in a similar way to Worbin’s previously-defined variable ‘surroundings/ambience’ (see section 2.2.1), the relationship between the ambient temperature and the temperature provided by an activator. The design variable ‘ambient temperature’ relates, as the term indicates, to the temperature prevailing in an environment, whereas ‘surroundings/ambience’ appears to include a wider perspective on conditions, such as for example airflow. (Worbin, 2010, p.265) The term ‘ambient temperature’, as presented in this thesis, was chosen especially to underline the impact of environmental temperature fluctuations on the *sunlight’s heating ability* and therefore extend its ability to influence how the sun causes colour change of the thermochromic dyes. The impact of this variable varies in relation to the differences in magnitude between the chosen dye activation temperature and specific fluctuations in temperature within the environment, for example due to whether it is an indoor or outdoor environment, the geographical location of the textile as well as the time of day. Outdoor set-up B clearly provides a larger fluctuation in ambient temperatures, due to the geographical location of the textile as well as time of day, compared to indoor set-up A that generally presents a more stable temperature environment.

4.4.6 *Design variable: Distribution of the sunlight*

The design variable ‘distribution of sunlight’ determines the area of the printed surface that changes colour, as well as the origin of the heat-spread across the textile sample. Observations demonstrated that sunlight acts as a heater over a large area. Sunlight heats all the illuminated areas printed with thermochromic dyes, rather than simply one individual

part of a chromic imagery. Colour change within an area-specific design requires to be created through deciding where, within the application, to print the thermochromic dye.

The samples investigated using outdoor set-up B, generally acquired a more or less instant colour change all over, without a directional origin of the heat spread, if the required activation temperature was reached. It appeared as if the entire sample had moved from inactive to active in an instant. A more directional movement of the heat spread (towards unlit areas of the samples), using the outdoor set-up, was observed if parts of a sample were shaded, and only later became illuminated (as was exemplified in Figure 4.33).

The indoor observations demonstrated tendencies whereby the colour change originated from the centre of the sample, with an even heat spread towards the edges of the samples (for visualisation see CD-ROM, Film 4 and Figures 4.61-4.66).

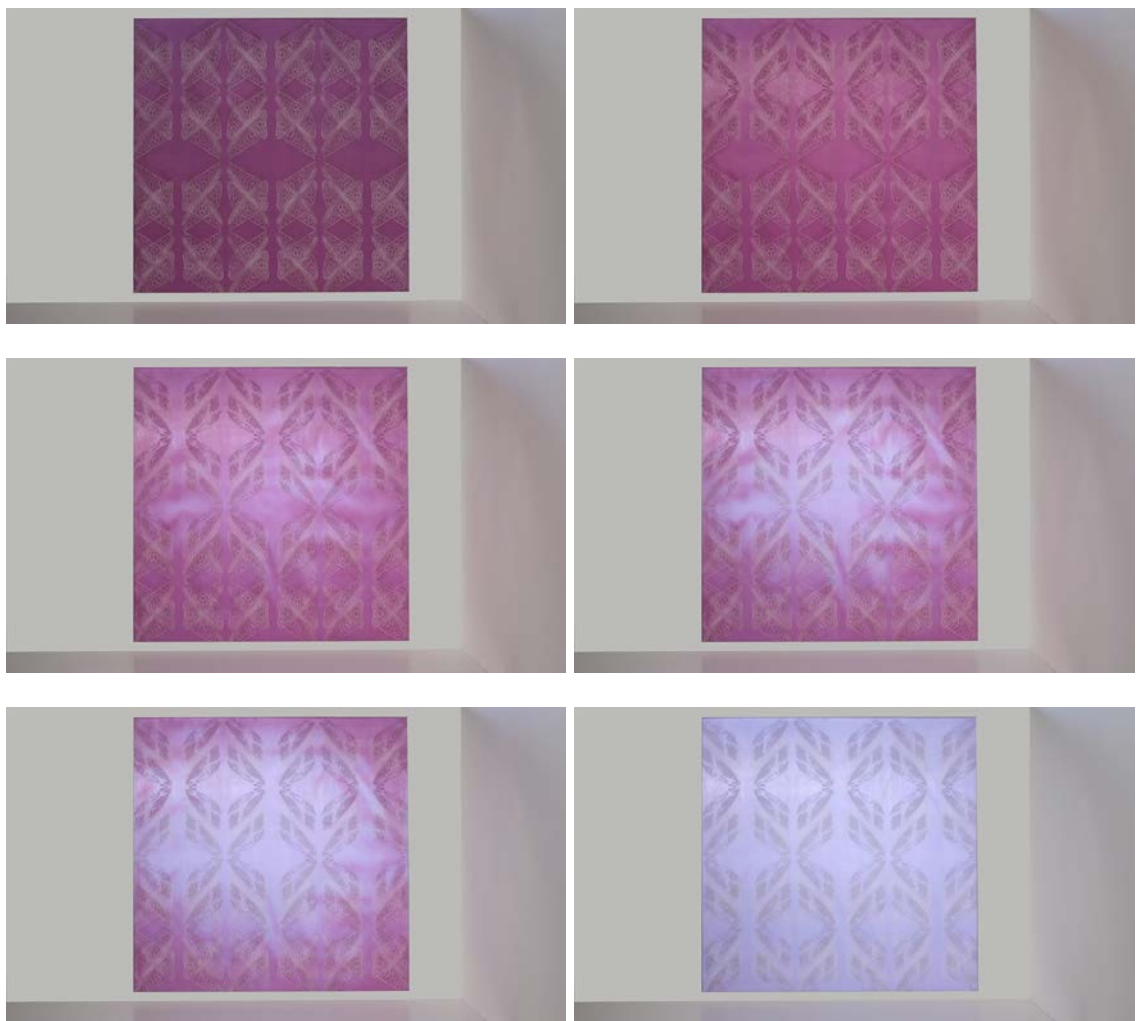


Figure 4.61-4.66 The origin of the colour changes of the thermochromic dye from the centre to the edges of the sample, when mounted on the windowpane, due to sunlight activation. (Photography: Film & Bildstudion AB)

This was considered to be due to the heat transferred by the window glass, and was consistent with measurements carried out during observations, which demonstrated that the centre of the sample generally had a higher surface temperature compared to the edges of the samples. As described above, the use of direct sunlight as an activator allows for design possibilities in which large areas may be heated without added components. This contrasts with the generally more complex situation when using incorporated electrical heating mechanisms, as is more commonly used. The latter situation requires additional incorporated materials, such as heaters, conductive wires/threads as well as an energy supply. Direct sunlight, therefore, provides a more environmentally friendly solution, especially when the design is intended to change colour over a larger area. Additionally, textile applications that use direct sunlight have less impact on the environment since they use a source of renewable energy, and also fewer raw materials compared to traditional electrical heating methods. Additionally, it is difficult to achieve large areas of colour change using electrical heating mechanisms, due to the practical difficulty of providing an all-over uniform current throughout the design. (Ledendal, 2009)

4.4.7 *Definition of a reversible dynamic imagery that is activated by sunlight*

This section describes how the descriptor for sun-activated textiles relates to the pre-defined descriptors for ‘reversible dynamic patterns’ within the field of colour-changing materials. The thermochromic dyes are dynamic, meaning that the chromic colour can reversely move from an inactive to an active colour state. The ‘reversible dynamic pattern’, defined by the description (*A B A*), by Worbin (2010), indicates that the design alters from one more or less static imagery to another. Nevertheless, the definition of the dynamic process is stated to have potential to change into one or several given possible expressions (Worbin, 2010, p.49). In this thesis, the following definitions are based on Worbin’s (*A B A*) definition, but with a number of amendments added to suit the specific applications when working with thermochromic dyes that are activated by sunlight.

One amendment is the definition of (*B_i*) rather than (*B*), where (*i*) stands for different possible outcomes of the expression of the imagery on the textile. The subscript (*i*) was used to emphasize a restriction in designing with thermochromic dyes that are activated by the sun. Variations in the expression (the different outcomes, *i*) may, for examples, be built up through the use of more than one dye with different

activation temperatures, in which case different expressions are created when a further activation temperature within the surface of the textile is reached. A chromic design that is activated directly by sunlight, is, however, unable, as discussed in section 4.4.6, to provide different expressions in selected parts of the printed surfaces that are heated (the sunlight heats the whole fabric). A more general definition of (B), as proposed by Worbin, might however, provide this possibility through use of other heating solutions. Furthermore, the thermochromic imagery that is printed on the sun-screening textile, as discussed in section 4.4.3, will alter depending of the particular sky condition (s) on a specific date (s^d) as well as the time of day (s^t).

A further amendment is a definition of the phase of the movement between colour states 1 and 2, when the dye exhibits the colours of the ‘transitional colour zone’ (see Figure 4.38), defined within this thesis as the ‘transitional colour phase’. This occurs due to the properties of thermochromic dyes, which cause them to change colour over a range of temperatures. The transitional colour phase is, contrary to the other amendment in this section, more or less relevant to all applications that use thermochromic dyes. The transitional colour phase can appear either more or less obvious, depending on the time interval (defined in section 4.4.2) and the temporal pattern (defined in section 4.4.3) of the colour change as well as the directional movement of the colour change due, for example as influenced by the distribution of sunlight (defined in section 4.4.6). The transitional colour phase was therefore considered to be of importance of the definition of any reversible dynamic *thermochromic* imagery. However, it is not stated that the observation of a transitional colour phase would be applicable to all dynamically reversible imageries, regardless of the particular dynamic material. The transitional colour phase is defined within this thesis as (T), included in this extension of Worbin’s ($A B A$) definition, as $\{A T B T A\}$. Thus, the conclusion from the research in this section of the thesis has led to definition amendments that provide the following two descriptors for reversible imageries created with thermochromic dyes; the first activated by sunlight $\{A T B_i(s^{dt}) T A\}$ and the second (any thermochromic print) activated through an undefined activation method $\{A T B T A\}$.

4.5 Comparison of printed thermochromic dyes that are activated through sunlight, body heat or by a heat circuitry

This section presents a comparison of three heating sources (direct solar activation, body heat and electrically powered heaters). Body heat and electrically powered heaters

were chosen for comparison to direct solar activation on the basis that these have been employed previously as the main heating solutions for textile applications with thermochromic dyes, as discussed in section 2.1.5. The comparison was conducted as an analysis of how the three heating sources relate to the set of design variables that have a focus on direct solar activation, as defined in section 4.4. The comparison of the three heating sources described in this section is a preliminary evaluation, based on theoretical considerations and on the author's many years of experience with chromic materials, as well as a literature review of other designers' and artists' experience in this area. The analysis resulted in the definition of a second set of design variables; 'amount of thermal energy', 'heating ability', 'time interval/temporal pattern' as well as 'distribution of heat'. These design variables apply to activators for thermochromic dyes in a more general sense, since they discuss the universal behaviour of the dynamic colour change. These variables address the possibility of achieving the temperatures, as well as the temperature ranges, that need to be provided to activate a thermochromic dye in the way that is intended. Furthermore, the variables question the possibility to control the fluctuations of the colour change, in terms of time and length, to create the intended effect. Finally, the second set of design variables question the nature of the spread of the heat throughout the textile in relation to an intended activator. This will allow the designer to consider the aesthetic effects that heat spread, time, and temperature will have on the thermochromic colour change in relation to an intended imagery. In this way, this second set of design variables acts as a tool, to be used by textile printmaker practitioners, to provide information as to which heating solution might be suitable for use within a certain design application, for textiles printed with thermochromic dyes. The main contrast between the activation of textiles printed with thermochromic dyes using sunlight and using electrical heating circuits or body heat is the difference in the ability to control the heat output and therefore the colour change of the thermochromic dyes.

4.5.1 *Design variable: Amount of thermal energy*

The comparison of the ability to provide enough energy to activate the thermochromic dyes within the three systems resulted in the definition of the design variable 'amount of thermal energy'. This design variable defines the ability of the activators to produce the required temperatures so that the intended thermochromic dye/s will be activated as intended. The parameter involving the levels of thermal energy that the activator(s)

might produce is a feature that the author would recommend fellow designers to investigate at an early stage, since all applications with thermochromic dyes need enough thermal energy to initiate colour change.

The analysis of the three activators resulted in the following conclusions. The heating of printed textiles through solar energy relies on the presence of enough sunlight, as discussed in the design variable ‘amount of sunlight’, section 4.4.1. The design variable, ‘amount of body heat’ determines that a sufficient amount of heat is generated to reach the chosen activation temperature of the printed thermochromic dye through the body temperature of the individual touching the textile. The design variable ‘amount of excess heat’ relies on that enough excess heat (thermal energy) is transferred from the electronic circuit to the printed fabric. The electrical system is naturally also dependent on the presence of a power supply. (Orth, 2003; Berzowska and Bromley, 2007, pp.4-5; LCR Hallcrest, n.d)

4.5.2 *Design variable: Heating ability*

The second design variable that was defined is ‘heating ability’: the ability of a heat source to provide a *specific temperature range* in order to reach the chosen activation temperatures of the thermochromic dyes. This variable becomes of importance if the designer intends to acquire control over the colour changes, i.e. when colour stages 1 and 2 are to start and finish, as well as the time interval of the transitional colour phases. The choice of activator will be directed in this way, since the analysis that has been carried out demonstrates that different activators allow for different levels of control.

The analysis of the three activators resulted in the following conclusions. The heating ability of solar energy partly depended on whether an indoor or outdoor application was used, as defined within the design variable ‘ambient temperature’ in section 4.4.5. The heating ability in the outdoor applications (set-up B) was particular dependent of the fluctuations of the ambient temperature, due to the specific geographical location, the orientation of the application (i.e. the angle and placement of the fabric) as well the time of day. The heating ability, in the indoor application (set-up A), demonstrated more dependence on the strength and reach of the sunlight, and thus its ability to heat the fabric as well as surfaces in contact with the textile sample (i.e. a windowpane), in relation to the ambient temperature.

The heating ability when using body heat will be dependent on the body temperature of the user and the activity that individual is carrying out (e.g., running vs. sitting). The heating ability when using an application with energy from an electrical heating circuit will primarily be dependent on its power output, which is related to the resistance of the heat circuitry. The power output will differ greatly depending on the design and the material used in the electrical heating circuit. (Berzowska and Bromley, 2007, pp.4-5; Harrop, 2009a and 2009b; Van der Maas, n.d. pp.8-9; XS-Labs, n.d.)

The heating ability of the three activation systems differs in their potential for optimisation to provide a more controlled colour change. In this regard, the heat circuitry differs compared with the other two heating methods. The potential to optimise a heating circuit, and therefore control it within a textile application is obviously feasible technically. Such optimised solutions have the possibility to be designed by the textile printmaker practitioner or through multidisciplinary collaborations. Similar optimisations of the other two heating solutions present more difficulties for the textile printmaker practitioner to control. The strength and duration of sunlight conditions rather relates to external factors, such as the sky conditions and geographical location of the textile. These are factors that cannot be optimised within the actual textile application. The heating ability of the body, relating to human physical factors, may be modified by variation of the body temperature, e.g. the user conducting physical exercise.

4.5.3 *Design variable: Time intervals/temporal pattern*

The third defined design variable, in reality a pair of related variables, ‘time intervals/temporal pattern’, highlights the fluctuations of the colour change, in terms of specific times as well as length of time. The ‘temporal pattern’ of the thermochromic colour change, as explained in section 4.4.3, is built up using combinations of the ‘time intervals’ (see section 4.4.2) of the colour change (t_1^{i-a} and t_1^{a-i}) and the periods of inactive (t_2^i) and active (t_2^a) colour states. These two individual variables were, in the interests of clarity, already introduced in sections 4.4.2 and 4.4.3, although they are variables that apply in the more general sense. The designer needs to consider the time interval and the temporal pattern if he/she intends to create specific colour changing effects. Not only does this include effects that are more controlled and perhaps programmed in nature, but also those of a more random nature. The printmaker practitioner needs to consider the possible ways that the time intervals/temporal pattern

can behave in relation to the various activators and their effect on the intended expression of the colour change.

The analysis of the three activators resulted in the following conclusions. The main difference between the temporal patterns of the colour change provided by the three heating solutions is in their ability to be controlled by both the textile printmaker practitioner and by users. The possibility to define the start time and stop time for heat activation with the heating scenarios, as well as the possibility to control the speed of colour change is based on the ability to exert control over the 'time interval' and the 'temporal pattern' variables.

Neither sunlight nor body heat can be turned on or off like a switch, unlike the electrical heating circuit. Using sunlight leads to a random temporal pattern of the colour change, since the activation is dependent on sky conditions and time of day. These are factors that neither the textile printmaker practitioner nor the user can control. Heating using body heat provides a random temporal pattern, as seen from the perspective of the textile printmaker practitioner. The scenario has, however, an ability to be controlled by the user to some extent. This heater is active when the textile is in contact with the human body, and inactive when there is no contact. (Berzina, 2004, pp.243-258; Tokyo Fibre, 2007, pp.126-133) The user can actively control this by choosing to wear or touch the textile. (Hodge, 2009; XS-Labs, n.d.) However, it is more difficult for the textile printmaker practitioner to exercise the control over the activation in such applications.

Heating circuits differ in some respect from the other two heating solutions, due to the possibility of creating not only controlled activation applications but also applications built on chance. Systems using heat circuits can be created, using integrated software that controls the energy flow and thus the temperature profile within the heat circuit, in order to provide control of the colour change. (Orth, 2003; Robertson, 2011) Such a system can be designed so that it may be programmed by the textile printmaker practitioner as well as the user, depending on the needs of the application. (Berzowska and Bromley; 2007, Worbin, 2010) For example, the software may be programmed to open and close the electrical circuit at fixed intervals. The programming might incorporate random variables, in order to provide a heating solution that consists of a combination of random and controlled variables. An example of the use of such a random variable would be a movement sensor, which is programmed to alternate the heat circuit between open and

closed every time a specific number of people have passed the sensor. The time taken for the specific number of people to pass the sensor corresponds to the random input, whereas specifying the number of people that have to pass in order to activate the programmed action corresponds to the controlled input. Design solutions using heating circuits might also provide systems of a more or less completely random nature. An example is a system where a manually operated switch controls the activation. In this way the user interacts with the system in a non-systematic way. Using the heat circuitry solution in this random way will result in the textile printmaker practitioner losing control over the time interval and temporal pattern of the colour change of the thermochromic dyes resembling the situation with sunlight activation.

4.5.4 *Design variable: Distribution of heat*

The fourth and final general design variable defined in this thesis is ‘distribution of heat’. The design variable ‘distribution of heat’ applies to the spread of the heat, in turn giving rise to the spread of the observed colour changes, due to temperature differences over the textile surface printed with thermochromic dyes. *How* the colour change will move in relation to a printed thermochromic imagery is a factor that will have a highly significant impact on the aesthetic expression of the design. Therefore, this becomes an important feature for designers to consider. Different activators distribute heat in different manners. For example, will the colour change appear all-over the textile surface at the same time, or will it originate from a particular point, such as from the sides or centre of the textile? Further, will the colour change follow a linear pattern or will it follow that of the shape of the elements of the printed imagery pattern?

The analysis of the three activators resulted in the following conclusions. The heat distribution differs using the three heating solutions. These differences depend on the contact surfaces of the printed textiles as well as the heating ability of the particular heating solution. The difference also depends on more specific variables, such as the shape of the heat source, e.g. the wide nature of sunlight distribution compared to the possibility of a heater in the shape of the imagery as is possible, either completely or in part, within the other two heating solutions.

The imagery that appears on the colour changed area is related to the distribution of heat through the printed surface. Compared to sunlight and, in some respects, body heat, the electrical heating circuits may be designed, for example, as a small dot or a

thin line. (Berzina, 2004, pp.175-176) This provides the possibility for the textile printmaker practitioner to control the design of the imagery of the colour changed area. The design can be controlled both through the choice of the shape of heat circuitry as well as through the design of the printed pattern using thermochromic dyes. In contrast, the use of direct sunlight heats all the illuminated areas more or less at once, as discussed in section 4.4.6. The imagery created using the body as a heater creates a third alternative, where the shape of the heat spread is defined both by the areas of the textile that are printed with thermochromic dyes as well as the shape of the parts of the body that are in contact with the printed fabric. (Berzina, 2004, pp.243-258; Tokyo Fibre, 2007, pp.126-133) The latter solution can create a variety of imagery. However, compared to the heat circuitry solution, the textile designer would not have the ability to control the variable while the user would gain control.

A conclusion from the results of the theoretical and experiential research described in this section is that it will probably be easier to change the colour of larger areas printed with thermochromic dyes using sunlight, and to some extent also body heat, compared to a heat circuitry solution. In the first two cases, no extra application needs to be fitted into the design, to create a large scale heating system. Heating circuits would also need to deal with the complexity of construction to provide a resistance that can produce sufficient heat over the entire surface. The use of the body as a heater restricts the size of heated area to the area of body that is in contact with the printed fabric. Therefore, the sun offers some considerable technical advantages as a heating solution, as well as its obvious environmental advantages.

4.6 Placing the design variables into context

The main contributions of this chapter are the definition of ‘design variables’, to expand the aesthetic vocabulary for designers using thermochromic leuco dyes, as well as amendments proposed to existing (see section 2.2.1) descriptors for ‘reversible dynamic pattern’ found in the literature. This chapter presented two different levels of sets of design variables: one level concerning activation of the thermochromic dye in general (section 4.5) and one level specifically concerning direct solar activation (section 4.4). The following sections explain how a designer within the design process could use these variables.

The *decision concerning choice of activator* will be guided by the set of more general design variables, defined in this thesis as ‘amount of thermal energy’, ‘heating ability’, ‘time interval/temporal pattern’ and ‘distribution of heat’ (sections 4.5.1-4.5.4). The designer will provide information related to the activation for the intended expression/product by discussing and ‘answering’ questions, which arise during the analysis of the intended expression of the colour changing design. This will result in a ‘framework’ of requirements for the activator with the aim to reach the intended aesthetic expression of the colour change. Questions that might be answered include the following;

- What are the demands (for example required maximum and minimum temperatures, temperature curves, accessibility of the thermal energy, portability of thermal energy produced) on the production of the thermal energy so that the intended design may be activated satisfactorily? Do these demands differ for different parts of the textile (for example is more than one activation temperature used) or are there only one set of requirements?
- In terms of time, in what ways should the colour change fluctuate (dependent on time, temporal pattern and spread of colour change)? For example, should the temporal pattern exhibit a slower or a quicker tempo?
- How should the relationship between the form and shape of the entire printed thermochromic imagery of the textile and that of the individually colour changed areas be displayed?
- Is the aim to control the colour change or should it be more random? Should different parts of the colour change be controllable and others more random?
- Is the design location-specific, and in that case how does the environment (ambient temperature, geographical position etc.) influence the design output?

Clarity of the intended activation scenario can be provided for the designer by introducing these design variables at an early stage of the design process. Defining this framework for what the designer is aiming for in terms of the aesthetics will steer the choice

of activator, since a number of activators will not be applicable to create the specifically intended expression, due to their specific limitations.

The second set of design variables will guide the printmaker practitioner to understand *how* to execute enhanced control of the aesthetic outcome when working *with direct solar activation*. The set of design variables defined (in section 4.4) as ‘amount of sunlight’, ‘time interval’, ‘temporal pattern’, ‘contact surfaces’, ‘ambient temperature’ and ‘distribution of sunlight’ will provide information as to *how* direct solar energy relates to the interaction with thermochromic leuco dyes. A designer’s intended expression/product of a textile using thermochromic dyes that are activated by direct solar energy is dependent on both the properties that the designer can influence (choice of ambient temperature, colour, shape of design element) and those that he/she may not, either in part or fully, be able to influence (geographical position as well as weather). The designer can provide information as to how to increase control of the design, by ‘answering’ the questions that are raised in relation to the set of design variables defined specifically for direct solar activation. Some questions might be answered more directly through an analysis of the intended aesthetic expression, while others might demand actual experimentation, so that the designer fully understands how a specific criterion effects an intended end result. Potential questions to be answered relating to direct solar activation could be;

- Will the textile be displayed indoors or outdoors? Will the sunlight have the possibility to reach the textile, so that enough thermal energy can be produced?
- Will the activation of the textile be increased by any contact surfaces, if so how will this affect the heating profile of the textile?
- From the point of view of the aesthetics, how can the designer take advantage of the fact that the tempo, activation and deactivation of colour change are more random in nature when using direct sunlight?
- Should the entire textile change colour or only parts of it? How can the designer utilise the wide nature of the spread of the sunlight, when activating the printed imagery?
- Is the design intended for a location-specific application and, if not, what information from the questions above is still relevant to the designer?

Chapter 5 Utilizing sunlight to create added aesthetic qualities, due to light translucency within the substrate materials

In the research described in this chapter, the aim was to answer the question as to whether sunlight, used to activate thermochromic leuco dyes that are printed on sun-screening textiles, could also be utilized in combination with surface treatments (devoré print and/or laser technology). The aim was to create additional aesthetic qualities and effects in a three-dimensional space as well as on the textile surfaces using a low-technology alternative approach to activation (research questions Q5, section 1.3). Compared to conventional electrical heating mechanisms, the low technology alternative aimed to minimise the use of electronics and to ease recyclability of the design. Furthermore, this chapter presents a discussion as to whether the additional sunlight-related qualities and effects achieved displayed a similar or different dynamic behaviour compared to sun-activated thermochromic dyes, established in the context of descriptors for reversible dynamic patterns (research questions Q6, section 1.3).

The investigations described in this chapter (part II) feed into the investigations referred to as parts I and III in this thesis because the additional aesthetic qualities and effects that were created are by-products of using solar energy (direct or indirect) as an activator for the thermochromic dyes. The investigations in this chapter are divided into two groups (parts IIa and IIb). The first part focuses on the dynamic aesthetics created by combining laser technology and/or devoré print with the colour change created by thermochromic dyes activated by sunlight (part IIa). The second part is an in-depth study into the potential to design imageries that cover several levels within a three-dimensional space (part IIb). These imageries are created due to the interaction between sunlight and a textile when solar energy is used as an activator for thermochromic dyes.

The first group of experiments and observations (part IIa, sections 5.1-5.5) resulted in new aesthetic findings; it was possible to produce large textile pieces that changed *both* in terms of colour and imagery without an additional energy supply. The effect was created using varying layers of laser technology together with printed thermochromic layers. The investigations into surface treatments also resulted in the finding that there exists a synchronised temporal pattern between thermochromism and the light and shadow imageries created via the laser and/or devoré treated imagery elements of textiles when using sunlight as the activator. The conclusions from these

aesthetic elements provide designers with examples of how to construct more complex dynamics when sunlight is integrated in the design.

The second group of experiments and observations concern an investigation of the potential to design imageries that cover several levels when operating within a three-dimensional space (part IIb, sections 5.6-5.8). These resulted in the definition of ‘an extended imagery’ (consisting of ‘the physical textile’, ‘the intermediate zone’ and ‘the incident surfaces’). Sections 5.6-5.7 demonstrate how the designer’s decisions concerning the construction and design of the physical textile, can, in addition, be used to achieve intended expressions and functions within the other two connecting levels. Section 5.8 discusses how these levels interact with one and another. The ‘extended imagery’ was included in the thesis to demonstrate that textile designers can actively address, not only functions, but also extended aesthetics by working with all, or parts of, the three levels of this extended imagery.

Additionally, the in-depth experiments and observations conducted in part IIb resulted in the definition of a set of key variables (movement of position of imagery, direction of movement within imagery, and composition). The aim was to provide designers with variables to consider when designing a textile that provides sunlight projection so he/she can gain more control over the design outcome of the light and shadow imageries projected on the incident surfaces. This chapter provides a means for designers to obtain a deeper understanding of the effect on the aesthetic outcome derived from the shape of the projected light and shadow imageries by studying *how* the cycle of movement of ‘the position of the light and shadow imagery’ behaves in relation to cycles of sunlight (both daily and yearly), and how this behaviour causes changes in the shape of the projected light and shadow imageries. These effects are based on the choice of the design of the imagery, exploiting the translucency of substrate materials or the shape of the outline of the textile that is projected by the sunlight, as defined in section 5.6.2. Section 5.6.3 contextualises these results using a conceptual street scenario to demonstrate how the position of a design (laser-cut imagery [a] and [b] in Figures 5.66-5.94) of the textile can be used to vary, not only the expression of the projected imagery but also the ‘connection’ between the physical three-dimensional space and the projected imagery, as well as creating variety in the tempo of the movement of the projected imagery. Furthermore, the findings described within this chapter provide the designer with information as to the impact that the chosen design,

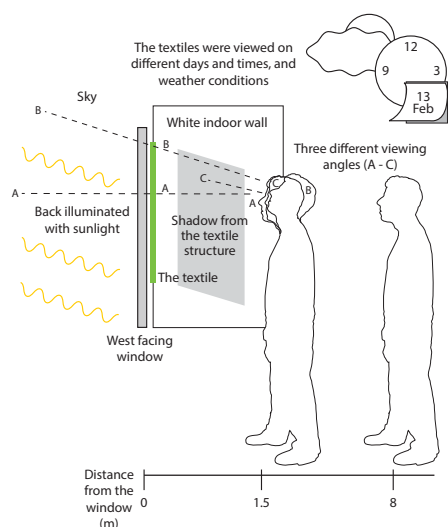
both composition and shape of design elements of the textile, will have on the *directional movement* of the design elements both ‘within the imagery’ as well as ‘within the composition’ of the light and shadow imagery. The use of simulation in a daylight laboratory⁶ (set-up E, see Graphic 5.3) was found to be highly successful in this phase of the research. This approach is therefore recommended as a fruitful means for textile designers to model and explore visual effects when investigating an intended textile imagery design in such a situation.

This chapter also explains how the descriptors for sun-activated thermochromic dyes, defined in section 4.4.7, require slight modification when the sunlight projected light and shadow imageries are defined. In contrast to printed thermochromic imageries, the projected light and shadow imageries are dynamic both in the sense that they can transition between a thermochromic inactive state and an active state, and also that they project a pattern on a surface, which changes during the day and throughout the year. The conclusions of this study are that the two versions of imageries, the printed thermochromic and the projected light and shadow imagery, display dynamic characteristics that are similar in some ways in the presence and absence of sunlight. However, the temporal pattern of the projected imagery is primarily controlled by the progress of time from sunrise to sunset, although particular sky conditions, for example lightly cloudy or heavily overcast sky, can also create variation within the daily cycle of the projected light and shadow imagery.

The experimental work involved in part IIa, which is analysed in sections 5.3.1, 5.3.3, 5.4.3-5.4.6 and 5.5, was carried out using a set of around 345 laser treated and/or devoré printed samples (around 130 devoré printed, 85 laser etched, 100 laser-cut and 30 with a combination of all techniques). The majority of these samples were constructed in combination with printed thermochromic dyes. A substantial selection of the approximately 345 surface treated samples were observed using indoor set-up C (see Graphic 5.1). Observations were carried out in a controlled manner, as with the observations using set-ups A and B (as illustrated in Figures 3.11-3.12). For example, the distance between observer and sample, the specific position of the observer and the sample so that the sunlight passed through the textile sample were all kept constant.

⁶ A daylight laboratory is a room with technical equipment that can simulate the sunlight, the path of the sun, colour temperature and sky conditions, at any geographical position on earth, which is normally used in architecture.

Additionally, set-up C contained a flat white surface, located to the right of the observer, which acted as a screen for projections, in order to ensure clarity in evaluating the movements and changes of the light and shadow imageries.



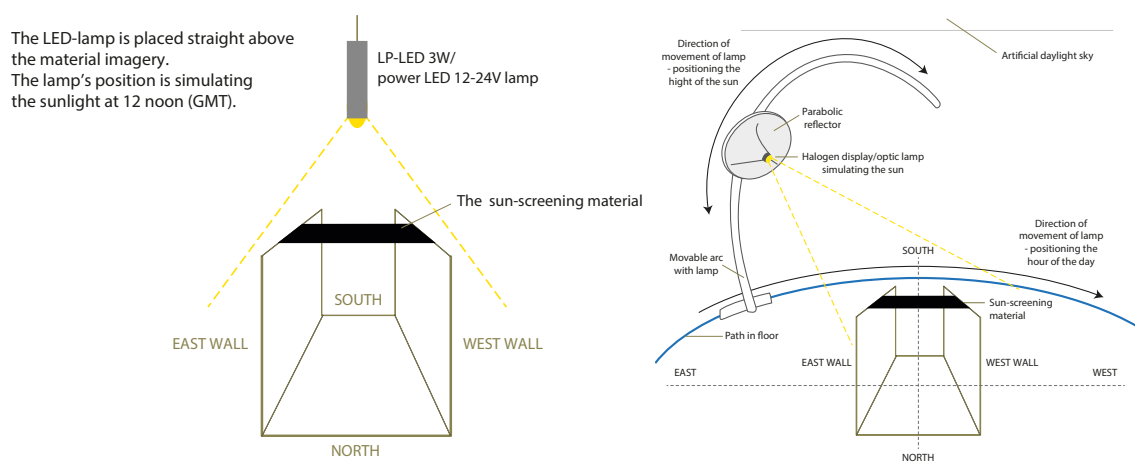
Graphic 5.1 Indoor set-up C, for observing samples that have been laser-treated and/or devoré printed.

Samples were observed under two daylight conditions: sunny and cloudy sky (see section 3.7.1). An evaluation of the percentage of cloud coverage of the sky as well as measurements of the illumination were carried out during each individual observation, in order to assign a specific sky condition. This chapter contains a summary of the key points of the analysis of how the laser- and/or devoré-treated surfaces of the textile samples were perceived to behave during the observations in sunlight (sunny sky conditions) in relation to the observations in reduced sunlight (cloudy sky conditions). The analysis is strengthened by a selection of representative photographs, which were taken during more than 500 observations.

Additionally, parts of the experiments of the investigations involved in part IIa were validated using laboratory measurements of the light transmittance values using a spectrophotometer (as described in section 3.10). The use of this method provided quantitative information on the amount of incident light that a laser etched and/or devoré printed area would allow to pass through (see sections 5.3.2 and 5.4.2). For example, information was provided on how much light the treated surfaces let through compared to untreated surfaces.

Furthermore, the spectrophotometer was used for measurements of the light transmittance values of the selected four untreated substrates as well as seven

monochromatically printed medium-thick, plain polyester-viscose weave substrates in the selected colours of the pre-set colour palette (see section 5.2). This investigation was conducted to compare the effects of the light translucency of the surface treated areas of the laser treated and/or devoré printed samples investigated during the analysis phase. Additionally, the spectrophotometer was used to validate the initial data obtained using visual observation carried out with a sample printed with thermochromic dyes, to demonstrate that the thermochromic dye itself did not significantly influence light and shadow imagery depending on whether the dye is in its active or inactive state (see section 5.1).



Graphic 5.2-5.3 Observational set-ups D with an LED-lamp and E in the daylight laboratory.

The experimental work of part IIb, which is analysed in sections 5.6.2, 5.7 and 5.8, was carried out using set-ups D and E (see Graphics 5.2-5.3). The investigation was divided into two parts. The first part investigated the movement of the projected light and shadow imagery in relation to the laser-cut design on the sun-screening textile. In the second part, an investigation was carried out using a conceptual scenario to analyse the key variables that were defined during the first part. The conceptual scenario was an actual street in Seville, Spain (latitude 37.23°N; longitude 5.58°E), which is detailed in section 3.9. The scenario was constructed to form a framework (temperature curves as well as geographical position and layout of the street) for the investigation, to create parameters for the analysis. The two set-ups (D and E) were constructed using a scaled model of the street together with laser-cut designs of sun-sails made from black and white paper. The 1:20 model was constructed so as, in a manageable way, to provide an estimation of the impact of the imagery that would result in a full-scale textile design. The model included scaled people (with an average

actual height of 1.70m), in order to study the relationship between the sun-screening materials, the displayed imagery within the three-dimensional space and the human body. Set-up D (outlined in detail in section 3.7.4) had a fixed illuminative position, directly above the laser-cut samples, using a LED lamp as the light source (see Graphic 5.2). Set-up E (outlined in detail in section in 3.7.4) used a halogen display/optic lamp that was fitted on a 63cm diameter parabolic reflector, both of which were mounted on a movable arc in the daylight laboratory (see Graphic 5.3).

The paths of the sun, investigated in the daylight laboratory, were set to the daylight hours of the 20th and the 22nd days in each month, to provide an understanding of the effects derived from the daily path of the sun. The investigation covered all twelve months of the year to provide additional understanding of the effects derived from the yearly path of the sun. The research also included an in-depth investigation into the longest day of the year (the summer solstice), the 21st of June, to provide further information on the movement of the sun during the 24-hour period. The investigation was carried out using a set of over 200 laser-cut ordered compositions as well as loose elements. The designs were based both on simple geometric shapes (rectangles and circles) as well as organic shapes with higher levels of complexity. The ordered compositions were pinned, either at the same or at different heights, parallel to the street within the model, alone as a single sail or with two or three sails together to make a composition. The loose elements were moved around freely on a transparent acetate film that was placed across the street on top of the walls in the model. This process provided a highly intuitive method, which offered the possibility to sketch motifs both as seen on the sun-screening textile and as observed on the incident surfaces within the model. The pattern could be easily altered and rearranged until an appealing expression was created that had potential both as a two-dimensional design on the sun-screening textile and as ‘three-dimensional’ imagery projected on the walls and floor. An important conclusion from this research is that this constructed sketch process provides a useful tool for textile practitioners when creating textile designs that provide moving light and shadow imageries due to the presence of sunlight.

The investigation using set-ups D and E consisted of several stages of analysis. The first part of the analysis was conducted during the collection of data of the experimental process using the two set-ups. The investigation had a second deeper analysis phase based on photographs and video recordings of the collected data, data

that proved to be most valuable within the analysis. This in-depth analysis was divided into two separate analysis sessions of the first and second parts of the investigation.

5.1 The connection between light transmittance and the change of colour states of the thermochromic dyes

The conclusions of investigations described in this sub-section are that the thermochromic leuco dyes do not offer an opportunity to influence the light transmission properties when moving between activated and deactivated states. It was initially envisaged that the activation of the printed thermochromic dyes to cause colour change might also give rise to a change in light transmission properties. However, it was ultimately found to be necessary to create such translucent areas through surface treatments of the substrates, since the leuco dyes proved to be non-translucent, both in their active or inactive states (see Figure 5.1).

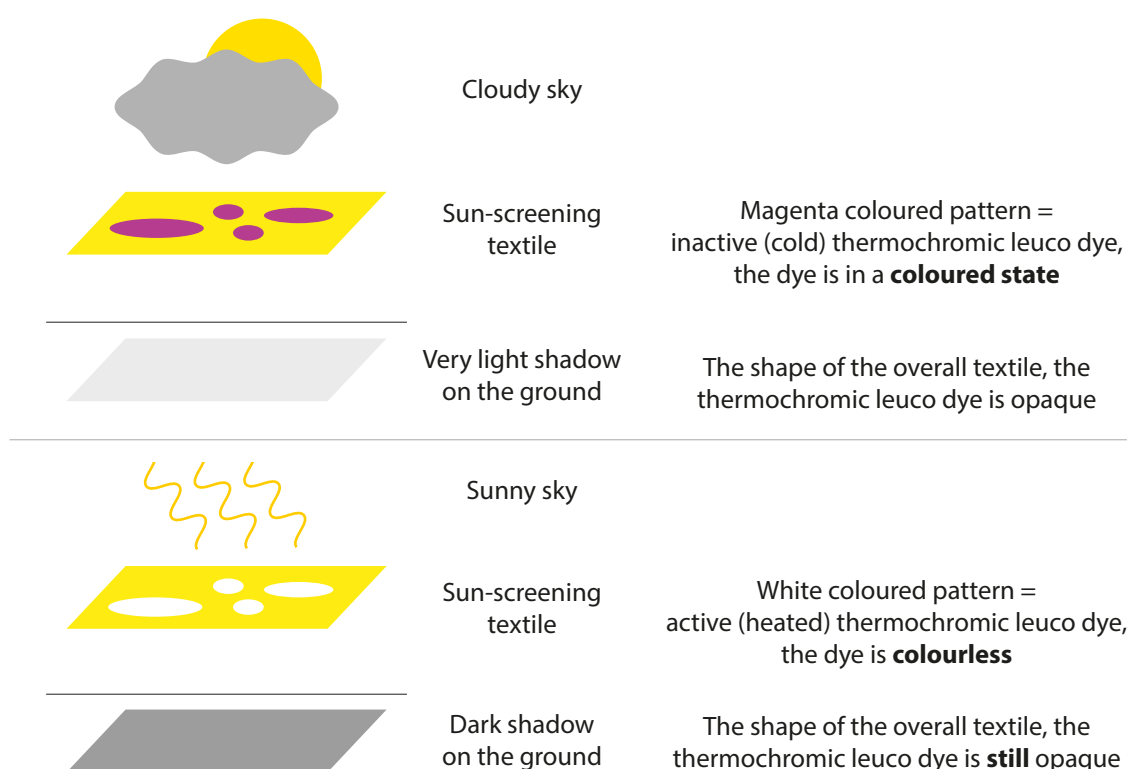
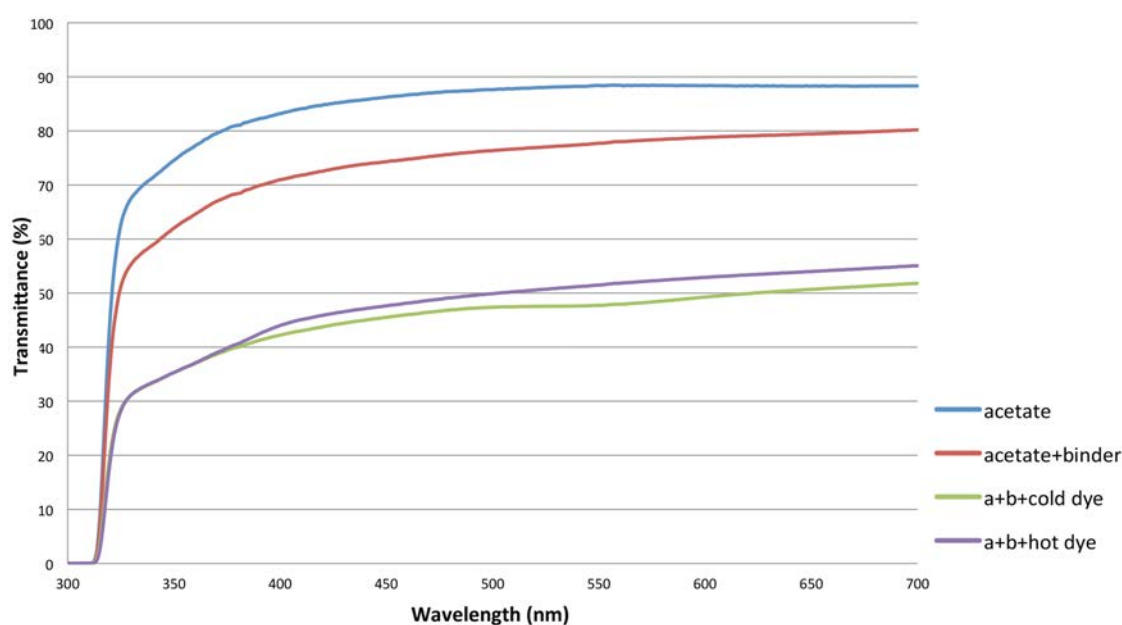


Figure 5.1 Illustrating the non-translucency of the thermochromic dye when the sunlight has heated the leuco dye in sunny sky conditions, as well as when it is unheated in cloudy sky conditions.

Initial tests were carried out using transparent monofilament weave and semi-transparent silkscreen T77 mesh (36.5-55.5%T, percentage transmittance) to demonstrate that the shape of the shaded area created by the sunlight did not alter significantly when the thermochromic dyes were activated in sunny sky conditions,

compared to inactive in cloudy sky conditions (see Figure 5.1). Only the intensity of the shadow altered with the light intensity. The thermochromic dye proved to appear colourless but not translucent in its active state. The substrates were printed with the colour magenta, using thermochromic dye supplied by Matsui, with an activation temperature of 27°C. The observation was validated by laboratory measurements of the light transmittance values, using the spectrophotometer, as described in section 3.10. The tests were conducted using a highly transparent material (around 90%T), an acetate film, to establish the influence on the translucency of the different variables. The following variables were tested: unprinted transparent acetate film, acetate film printed with pigment binder, as well as acetate film printed with the magenta coloured leuco dye.



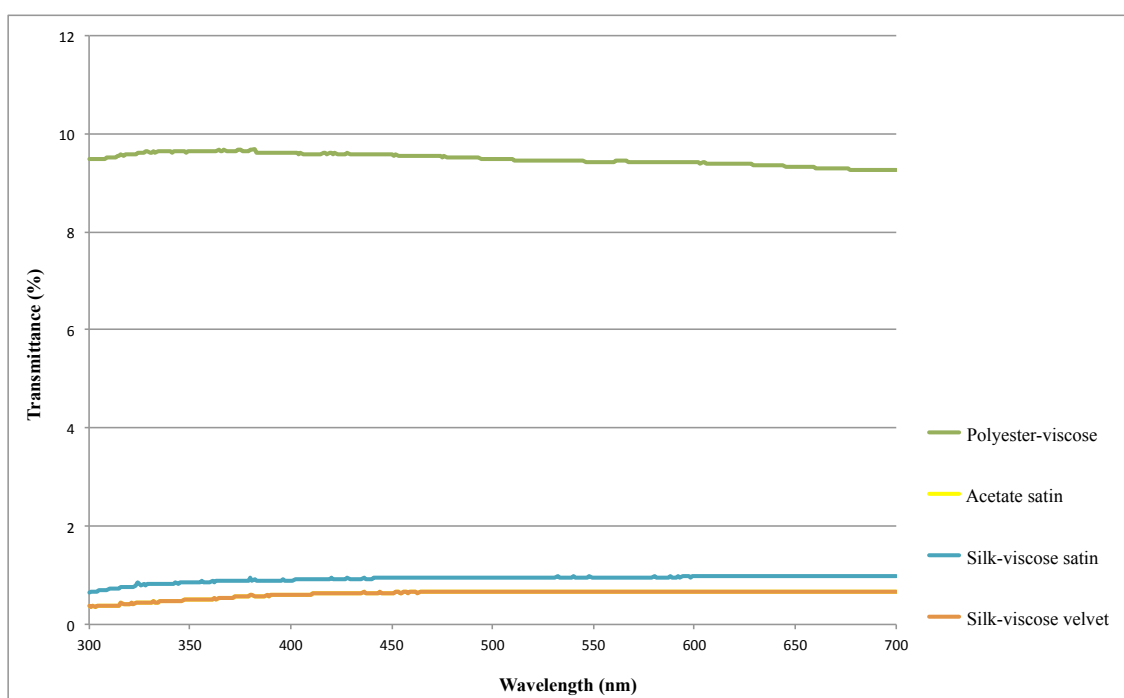
Graph 5.1 Amount of light transmitted through the acetate film.

The tests, as illustrated in Graph 5.1, demonstrated only a very small difference when the thermochromic dye was active (the purple curve) compared to when it was inactive (the green curve). The acetate film, printed only with the standard pigment binder into which the dyes were incorporated, was included to investigate if opacity was provided by the binder. The measurements demonstrated that the sample transmitted much more light when printed with only pigment binder. This confirms that the thermochromic dye is primarily responsible for the opacity in the prints. The outcome from these light transmittance tests led to the conclusion that the dyes did not offer the opportunity to influence translucency, and so a concept was formulated to investigate the potential offered by the overall shape of the sun-screening textiles, together with

light transmitting patterns created through textile printmaker practitioner related techniques, to create added aesthetic effects.

5.2 Substrates and techniques used in the investigation of the effects of translucency, due to sunlight

This section reports measurements of the light transmittance values of selected untreated as well as monochromatically printed substrates in the selected colours of the pre-set colour palette. The treatments of the surfaces included in the investigation used the following techniques: devoré print and/or laser-etch as well as laser-cut. Due to the focus on printed textiles in the research, it was appropriate that techniques were used for creating light transmitting imagery translucency through surface treatments with ‘off the shelf’ substrate fabrics, rather than through a textile construction technique (such as knit or weave). The techniques were chosen on the basis of an assessment of the potential for combination with imagery printed with thermochromic dyes.

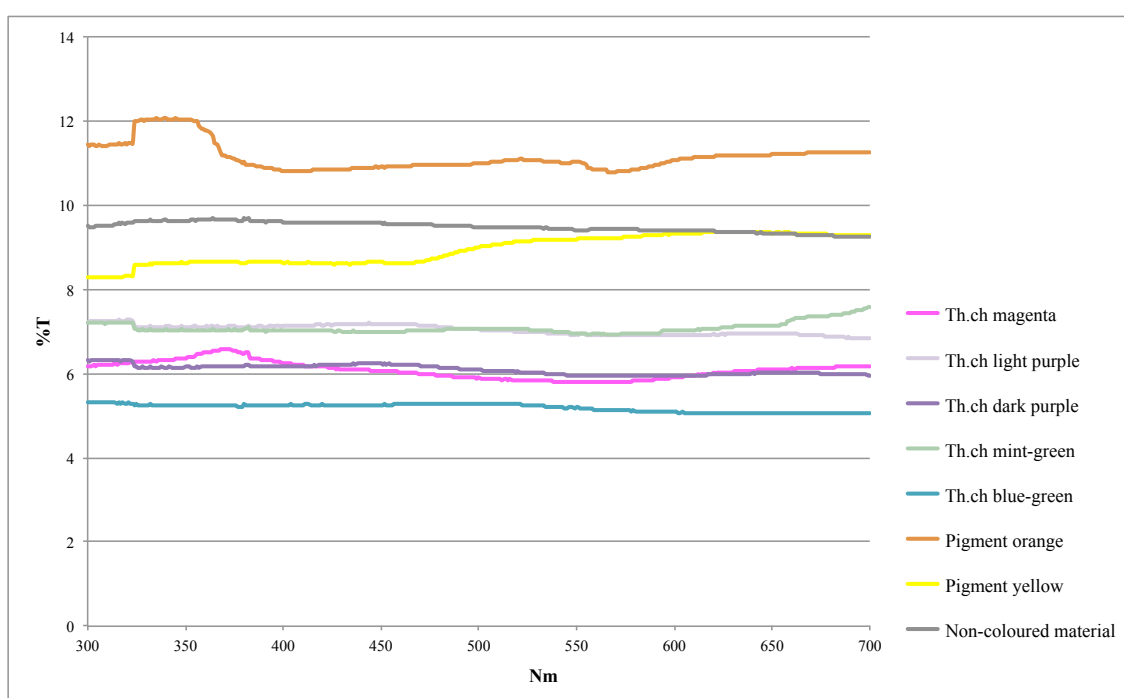


Graph 5.2 Light transmittance values (%T) of the selected untreated substrates.

The translucency of the different substrates (see Graph 5.2) used was measured with the spectrophotometer as before. A range of substrates with low initial translucency (polyester-viscose, acetate satin, silk-viscose satin and the silk-viscose velvet) was selected from the initial group of substrates described in section 4.2. These selected substrates showed a slight variation in light transmittance properties (see Graph 5.2). The thicker substrates (acetate satin, silk-viscose satin and silk-viscose velvet) provided

a transmittance of 0.5-1%T. The intermediate substrate, the plain polyester-viscose weave, provided a value of 9%T.

Samples of plain polyester-viscose weave were measured after being printed with the pre-set colour palette (yellow, orange, magenta, light purple, dark purple, mint-green and blue-green) to demonstrate the impact on the %T value of the dyes and inks from the pre-set palette. The polyester-viscose was chosen since it was the substrate from the selected material group that had provided the highest light transmittance value. It was therefore envisaged that this fabric would display most clearly the differences in the values of the light transmittance of the pre-set colours. The measurements of the printed samples demonstrated that most of the colours analysed decreased the light transmittance value by around 3-4%T (see Graph 5.3). However, the permanent yellow colour appeared to have little influence on the outcome while the sample printed with orange provided a higher %T compared to the unprinted sample.



Graph 5.3 Light transmittance values (%T) for plain polyester-viscose weave printed with the pre-set colours.

5.3 Devoré printing

This section presents the experimental work, analysis and conclusions of research using the technique of devoré print to create surface treatments for increased light translucency within parts of textile substrate. The photographs presented were selected to illustrate and support the analysis. The devoré print investigations resulted in the

observation of a temporal pattern synchronised between the sunlight-activated thermochromism and the light and shadow imageries created via the devoré treated elements of the textiles. Devoré printing is a technique, for method see section 3.5.3, used to burn away fibres selectively from fibre blends to create more translucent structures within a fabric substrate. Fibres from one of the blend components can be burnt away depending on the chemicals used in the dye recipe. (Kinnersly-Taylor, 2011, p.105) Devoré printing was, therefore, considered to offer the possibility of providing interesting aesthetic qualities, by creating ‘light imageries’⁷ at the textile surface, as well as partly letting sunlight pass through. The possibilities to create translucency with devoré techniques were considered compatible with surfaces printed with thermochromic dyes, in that both are printing techniques.

The initial samples were printed with only devoré paste to focus the outcome of observations on the effects of the devoré structure. Samples printed with thermochromic dyes combined with devoré were also investigated. This was carried out to demonstrate the effect on printed thermochromic dyes heated by sunlight, when the textile contained regions of different thickness. The samples, printed purely with acid-based devoré paste, which had provided an interesting result when sunlight passed through the textile, were later also printed with the thermochromic dyes (see Figures 5.2-5.5). The imagery was printed on the following substrates: silk-viscose satin, polyester-viscose and silk-viscose velvet.



Figures 5.2-5.5 Selection of samples printed with devoré as well as devoré and thermochromic dyes mounted onto a windowpane (set-up A). Figure 5.3 ‘Light imagery’ of the winged structure can be observed in the upper half of the textile sample, compared to the absence of ‘light imagery’ in the lower half of the sample.

⁷ ‘Light imageries’ are defined within this thesis as elements of imageries that are created on the surface of the substrate when sunlight shines through the textile, due to the fact that these areas are surface treated so that more sunlight may pass through compared to the rest of the substrate.

5.3.1

Observations in sunlight of samples printed with devoré

The following sub-section reports conclusions from the analysis of the observations of devoré printed samples. A substantial selection, roughly one third of the around 130 devoré-printed samples were observed in sunlight using the indoor scenario, set-up C, as defined in section 3.7.2 and Graphic 5.1. These observations were conducted to investigate other type of dynamic effects that textile printmaker practitioners may use in conjunction with the thermochromic effects when sunlight is used as an activator for the chromic dyes. The selection was based on the aesthetic level of interest within the sample as well as the potential to provide variations in the aesthetic expression. The observations focused on the ‘light imagery’ that was created within the textile sample when sunlight passed through the devoré-printed structures, see example in Figure 5.3, as well as the light and shadow imagery that was projected onto the white wall, see examples in Figures 5.6-5.12. The observations also included the selection of samples with different aesthetic see-through qualities, which were presented in section 4.2, as demonstrated in Figures 5.6-5.14.



Figures 5.6-5.7 (left) Pure devoré-printed silk-viscose velvet sample in sunlight as well as the shadow from the sample. Figures 5.8-5.9 (right) Pure devoré-printed silk-viscose satin sample in sunlight as well as the shadow from the sample.

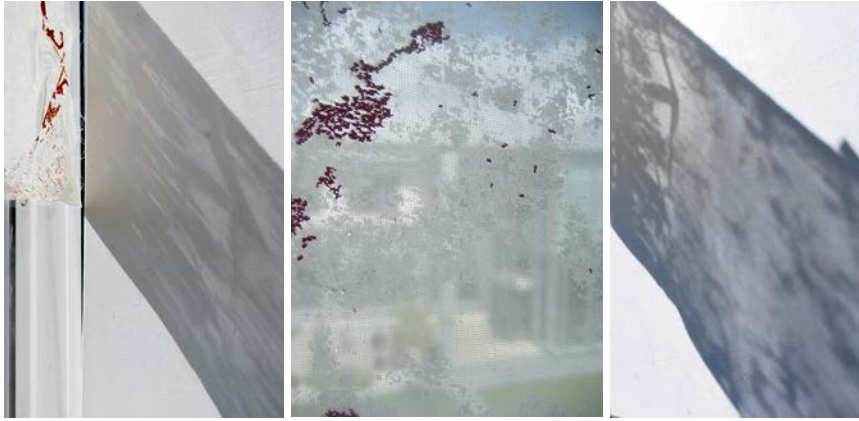


Figure 5.10-5.12 Devoré-printed silk-viscose velvet sample with almost no pile structures. Figures 5.10 and 5.12 The shadow created by the sample, in sunny sky conditions.



Figure 5.13 (left) Devoré-printed polyester-viscose weave sample with floats in sunlight, as well as the shadow from the sample. The floats in the shadow are visible in the sharp shadow closest to the printed sample, but the shadow becomes unclear further away from the sample where the floats are no longer distinct within the light and shadow imagery. Figure 5.14 (right) Close-up of the structure with floats.

The result from the silk-viscose velvet samples, which were devoré-printed on the face of the fabric, differed mostly from the others, due to their aesthetic expression involving a subtle relief structure. The sample acquired a soft feel, due to the fact that only half of the pile had been removed. However, the relief imagery appeared almost to disappear when the sample was mounted onto a window during sunny sky conditions. The polyester-viscose fabric created a structure with floats, in the devoré-printed area, which none of the other fabrics displayed (see Figures 5.13-5.14).

Shifts in the focal point were observed when the devoré-printed samples were back-illuminated with sunlight. The ‘light imageries’ created in the devoré-printed areas acquired a clearer focus in sunny sky conditions, and less clearly in cloudy sky conditions (see Figures 5.15-5.16). This creates an additional dynamic aesthetic

expression on the textile surface that designers can use as a complement to the colour dynamic that is created by the thermochromic dyes. The only samples that did not cause a clear shift of the focus involved the silk-viscose velvet. These samples still had a significant amount of full-length pile remaining in the devoré-printed areas. The surfaces appeared too thick to demonstrate ‘light imageries’ on the fabrics when back-illuminated. The inactivated samples printed with darker or more colourful thermochromic dyes, that were not mixed with permanent pigments, demonstrated a focal shift, moving from the printed surface towards a more even balance between the ‘light imagery’ perceived on the textile surface and the thermochromic dye when activated (white or light residual thermochromic hue).

The shadows created on the white wall in set-up C, when the sunlight passed through the devoré-printed samples, resulted in a two-shade shadow effect when observed in sunny sky conditions (see Figures 5.6-5.7). The shadow imagery provided through the devoré printed imagery created beautiful and interesting complements to the dynamics on the textile surface. The shadow provides an aesthetic extension of the textile printmaker practitioner’s constructed textile design. The contrast between the two shades was extended even further with the samples that combined devoré and thermochromic dyes.

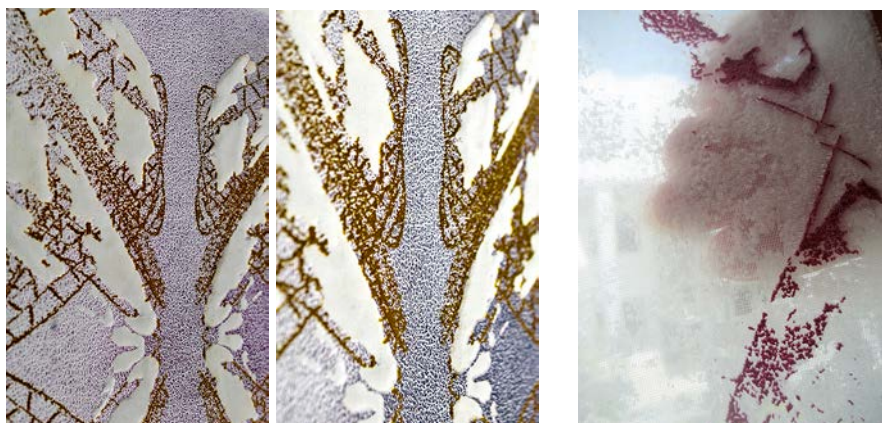


Figure 5.15-5.16 Close-up of devoré-printed imagery, during cloudy sky (left) and sunny sky (right). The ‘light imagery’ of the devoréd structure became more in focus when sunlight was intensified during sunny sky. Figure 5.17 Areas printed with magenta on the silk-viscose velvet sample, with a visual impression of partly being embroidered.

The result from the silk-viscose velvet samples provided yet another additional aesthetical expression, with the devoré-printed areas showing a good see-through quality. The areas printed with magenta gave the visual impression that they had been partly embroidered, especially in the printed thin outline areas (see Figure 5.17).

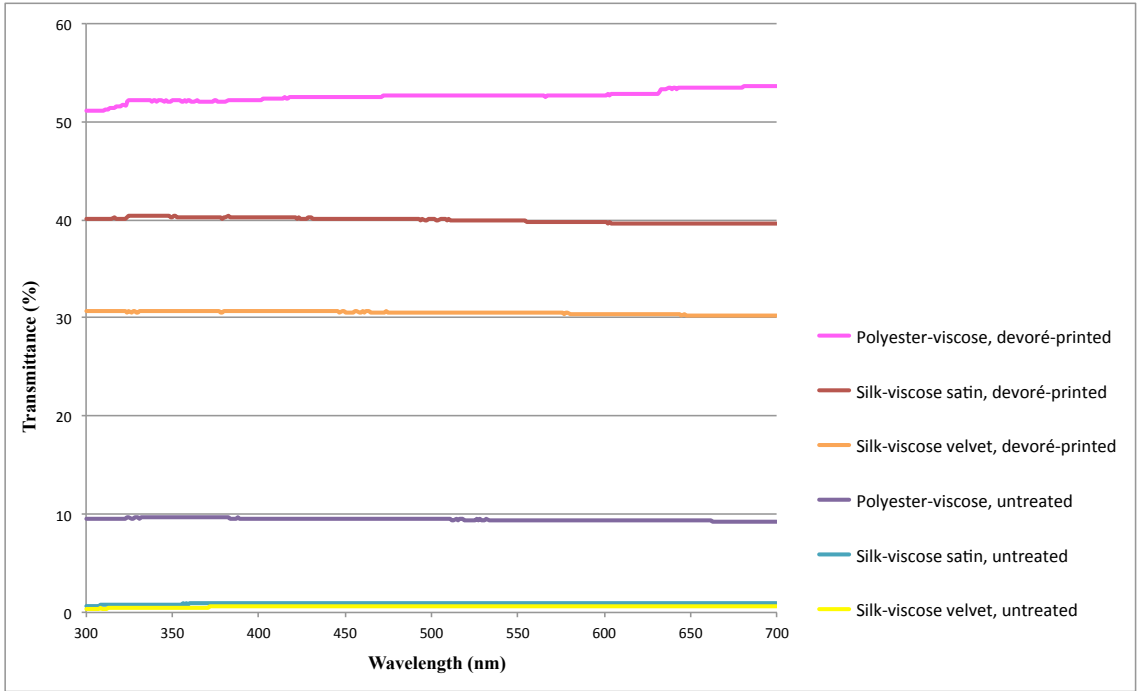
The tempo of the shift of the intensity of the light and shadow imagery projected on the wall, which are determined by the tempo of the changes in the sky conditions, resulted in a aesthetically interesting synchronised temporal pattern in relation to the colour change of the thermochromic dyes. The effect of activation and deactivation are in both cases dependent on the intensity of sunlight. CD-ROM, Film 3, part II-III visualises the temporal pattern of the projected light and shadow imagery as well as the synchronised temporal pattern between the thermochromic colour change and the projected light and shadow imagery (for studio set-up used see section 3.8 and Figure 3.19). The sample, mounted indoors onto a windowpane (set-up A), is printed with dark purple, that moves towards dark blue, as the thermochromic dye, with activation temperature 27°C, is activated.

The levels of distortion of the light and shadow imagery, projected on the wall, differ widely depending on angle of sunlight and time of day as well as the angle between the fabric sample and the white surface, within set-up C, onto which the imagery was projected. An extensive investigation leading to an in-depth understanding of the relationship between the position of the sun and the perception of the projected light and shadow imagery is described in section 5.6.

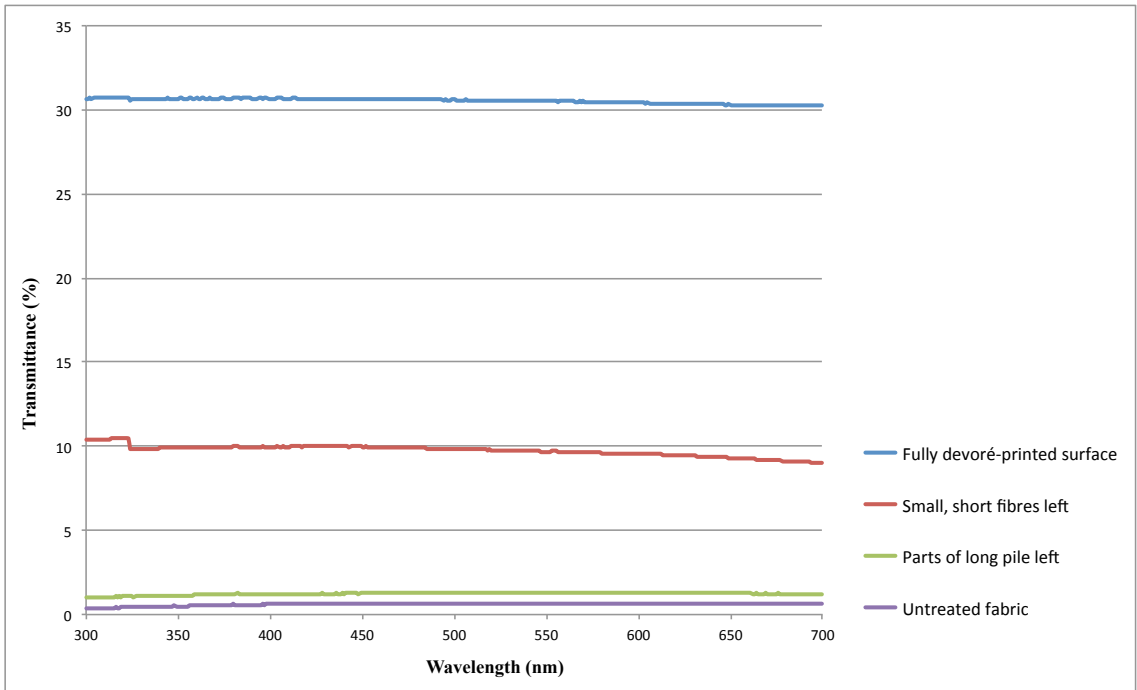
5.3.2 *Light transmittance tests on devoré-printed samples*

This sub-section contains the light transmittance data, which were used to investigate the relationship, in terms of the ability to screen off sunlight, between the devoré printed structures investigated compared to the un-treated substrates. Furthermore, light transmittance values provided an indication of the effect on light transmission that could be produced by a particular treated surface if it was a larger surface compared to the smaller surfaces previously prepared and observed visually. The light transmittance values of the devoré-printed fabrics were measured with the spectrophotometer in the areas of the fabric that provided a fully burnt-out effect (no fibre left within the measured area), so that the optimal transmittance effect could be assessed. The samples showed improved light transmittance (30-40%T), within the devoré-printed areas (see Graph 5.4). The untreated samples were, for comparison, measured on an unprinted surface (see Graph 5.4), since the dyes and the binder, as shown in section 5.1, had proved to reduce the light transmission (see Graph 5.3). The plain polyester-viscose weave sample, with floats, provided the largest measured increase, with a difference of 44.0-44.5%T (see Graph 5.4). The silk-viscose satin provided a difference of 39%T (see Graph 5.4). A

smaller increase in the light transmittance value was achieved by only partly devoré-printing the surface (see Graph 5.5), as carried out with the silk-viscose velvet samples Th.ch&Devoré-T3 and Devoré-T5 (see section 3.5.3 for explanation of sample codes).



Graph 5.4 The light transmittance values (%T) of the different devoré-printed and untreated substrates.



Graph 5.5 The light transmittance value (%T) of the different levels of untreated silk-viscose velvet as well as devoré-printed.

These samples gave, respectively, measured increases of only 9-10%T and 0.5%T, due to the fact that a short pile structure and parts of the long pile were still intact. This contrasts with the silk-viscose velvet samples that provided a fully devoré surface, which provided an increase of just around 30%T (see Graph 5.5).

5.3.3 *Conclusion of analysis of the samples devoré-printed*

The spectrophotometer tests conducted on the devoré-printed samples provided useful measurements of light transmittance, and the relationship between the different treated structures compared to the untreated substrates. The devoré technique added interesting dynamic aesthetic qualities to the overall expression of the textile, which the printmaker practitioner may use in conjunction with the colour dynamics of the thermochromic dyes. Incorporating the devoré printing technique also offers design possibilities for sun-screening textiles to create more intricate light and shadow imageries in the room or outdoors (on walls and the ground). Using the devoré print to modify the light-transmitting properties introduces only minor limitations to the design process when working with thermochromic dyes. The only direct limitation is the need to use substrates suitable for devoré-printing (see section 3.5.3).

5.4 Laser technology

This section presents the experimental work, analysis and conclusions arising from the use of two laser techniques (etching and cutting) to create surface treatments for increased light translucency within parts of the textile substrate. Selected photographs are, as in section 5.3, presented to illustrate and support the analysis contained in this section. This section presents the investigations, and discusses the results of the findings on the aesthetic possibility for producing large textile pieces that changed in terms of *both* colour and imagery without the requirement for an additional energy supply, through the use of laser etching in combination of thermochromism.

Laser technology is a technique (for methods and technical and information see section 3.6) used to either completely or partly burn away fibres within a substrate, with the use of a computer software controlled laser-beam. This process can either create a relief structure within the fabric surface or create more cut-through mark making. As with the devoré technique, it was envisaged that laser technology could be used to create light imageries on the textile surface, and translucent structures so that sunlight

could pass through the textile. The investigation described in this section includes exploration of the suitability of two related technologies: laser etching and laser cutting

5.4.1 *Laser-etch results*

This section presents the work carried out using laser-etching. The investigations of the laser etched structures commenced with an aim to establish the settings for the laser instrument that would create a fabric structure that allowed more sunlight to pass through, as defined in Q5, section 1.3. The selection of substrates (acetate satin, silk-viscose satin, silk-viscose velvet) were the materials that had proved most successful when printed with thermochromic dyes, and selection was based, as in the devoré investigation, on the initial investigation of the materials, as explained in section 4.2. Several settings were investigated for each fabric, using small step-by-step increases of the setting referred to as maximum power, to avoid the materials catching fire. In a number of tests, the lines in the etched structure were successfully made thicker by lowering the laser beam from a height of 12mm to 5mm above the surface of the fabric (see Figure 3.7). Several samples that were printed with thermochromic dyes prior to etching required a stronger power beam to provide a similar visual effect compared to when the same imagery was etched on the equivalent untreated white substrate (see Figures 5.18-5.19).

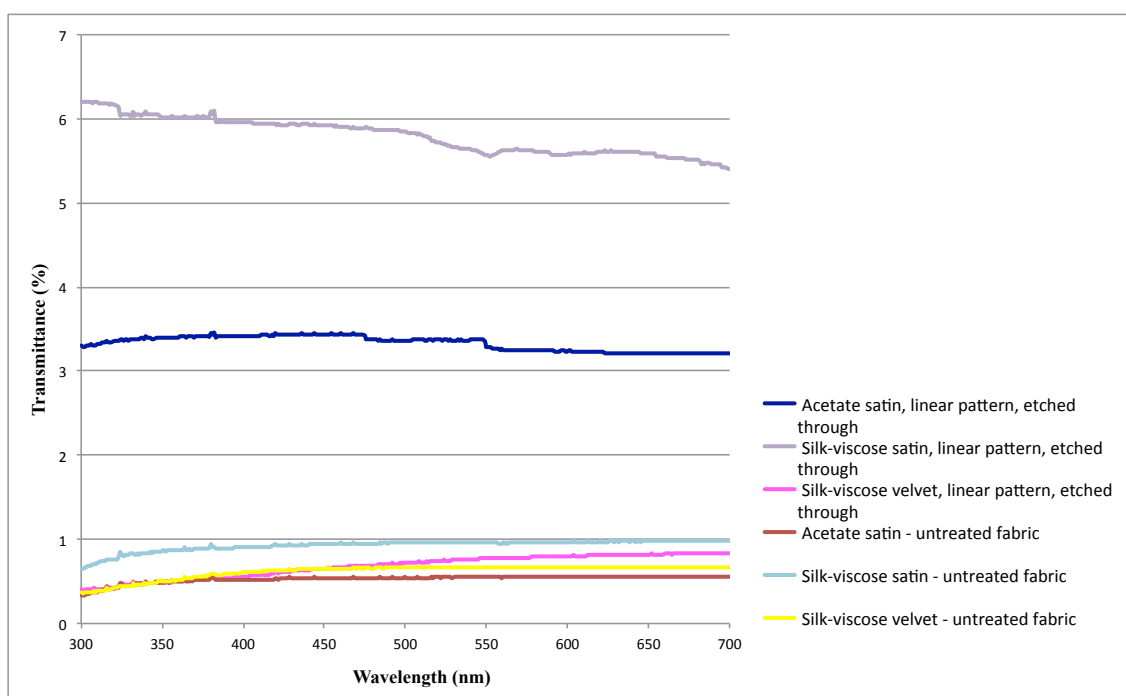


Figures 5.18-5.19 Silk-viscose satin printed samples that are first printed then laser-etched.

5.4.2 *Light transmittance tests on laser etched samples*

This section contains an evaluation of the light transmittance values obtained from the laser-etched structures. These values were used, as were the values for the devoré printed samples, to investigate the relative amounts of screened off sunlight of the different treated structures, compared to the untreated substrates. The light transmittance (%T) of the laser-etched structures was measured with a

spectrophotometer, as defined in section 3.10. The measurements were carried out on a selection of the successful structures from the total of around 70 samples created. However, only a slight increase in light transmittance was produced, assessed on the basis of the %T of the treated fabric subtracted from the %T of the equivalent untreated fabric. The largest increase was measured in the samples that were fully etched through. The acetate satin achieved an increase of approximately 3%T and the silk-viscose satin 4-5%T (see Graph 5.6). No notable improvement in translucency was found in the silk-viscose velvet samples (see Graph 5.6).



Graph 5.6 Plot of the light transmittance (%T) of the laser etched as well as untreated substrates. None of the samples are printed with dye.

5.4.3 *Sunlight observations of laser etched samples*

This section presents the initial outcome of the analysis of the observations of the laser-etched structures. A substantial selection of the etched structures was observed using set-up C mounted indoors on the windowpane, as defined in section 3.7.2 and Graphic 5.1. The selection was made based on the aesthetic qualities. The acetate and silk-viscose satin samples, with a fully etched-through structure, displayed slight, striped ‘light imageries’ (for definition see footnote, section 5.3) on the surface of the fabrics when the textile was back-illuminated with sunlight. However, the etched lined structures displayed neither any clear focal shift due to the ‘light imagery’ nor any clear light and shadow imagery on the incident white wall in set-up C used for the

observation. Instead, the samples created a solid shadow due to the overall shape of the textile. The samples produced using the laser etching technique with the intention to improve the light transmittance levels, were not providing the intended enhanced expression, and were therefore not investigated further.

5.4.4 *Aesthetic enhancements of surfaces printed with thermochromic dyes through etched imageries*

This section presents the second outcome from the observations of the laser-etched structures, which, after further investigation, established the aesthetic possibility of producing large textile pieces that change in terms of both colour and imagery, without the need for an additional energy supply. The analysis of the previous sunlight observations of some of the laser-etched samples, however, addressed the second part of the aim of research question Q5, section 1.3 in a way that was different from that described in section 5.4.3. When the acetate and the silk-viscose satin samples printed with thermochromic dyes moved between active and inactive colour states, a dynamic effect within the etched imagery, with interesting aesthetics, which arises specifically due to a combination of thermochromism and laser etching, was observed. The effect occurred in the area of the etched lines within the designs that were not etched through. The effect was considered to provide interesting additional possibilities in terms of aesthetic changes within the imagery, with the use of thermochromic dyes. In relation to the overall theme of this thesis of creating colour change on a surface printed with thermochromic dyes, when solar activated, this effect provides additional possibilities for the designer in enhancing the imagery dynamics, due to the use of solar activation of the dye. With the next batch of approximately 15 laser-etched samples, the focus was therefore on investigating how such laser-etched structures could be used to underline the effect within the imagery during the different phases of the thermochromic activation and inactivation process. The samples were printed with thermochromic dyes with one or more of the three different activation temperature (27, 31 and 47°C).

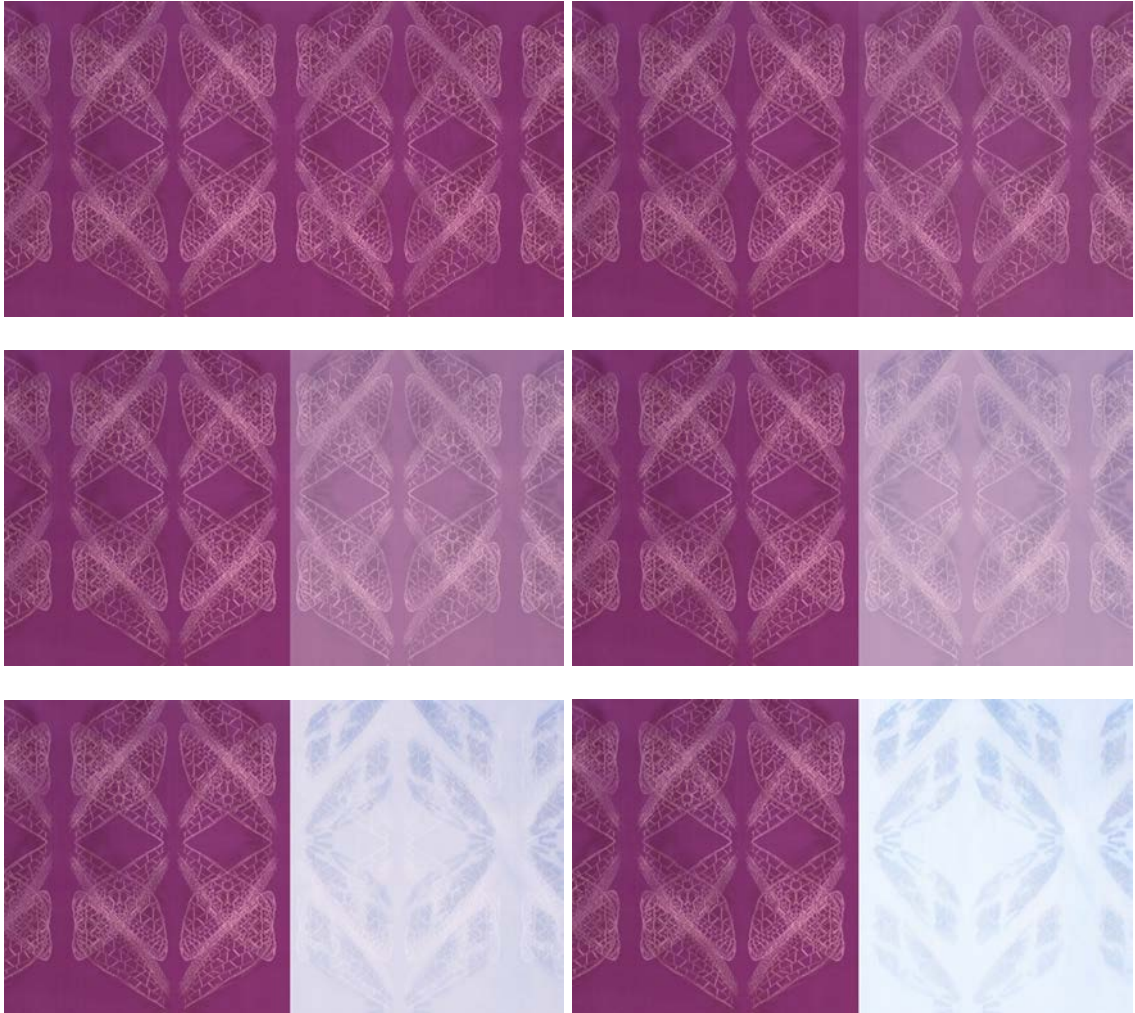


Figures 5.20-5.23 Acetate sample printed prior to being etched. Figure 5.20 (left) The etched butterfly image is visible when the sample is inactive (magenta coloured). Figures 5.21-5.22 (centre) displays the sample in the transitional colour phase, when the colour is moving from the inactive state (magenta) to the activated state (the white substrate colour) when back-illuminated. The etched imagery slowly becomes less visible. Figure 5.23 (right) The sample is fully activated and the etched imagery is almost invisible.

The acetate satin samples were all printed prior to being etched, as exemplified by the two samples in Figures 5.18-5.19. The technique provided a visible etched imagery when the printed magenta was inactive during cloudy sky conditions (see Figures 5.20). Both finer lined structures as well as larger areas that appeared more or less solid were visible. As illustrated in Figures 5.23, the etched imagery became less noticeable on the white substrate that resulted when the thermochromic dye was fully activated (the magenta colour moved to a colourless state). The change in the visibility of the etched imagery resulted in a slight change of focal point. The emphasis shifted from focusing on the etched imagery, in the inactive state (cold) of the thermochromic dyes, towards the non-etched areas of the substrate when the dye was activated (heated). The effect of a change in visibility of the etched imagery was observed also when the sample was changing from one printed colour to another (for example, from purple to blue), rather than from a colour to the white colour of the substrate, as in the previous example.

The silk-viscose satin samples demonstrated similar, but slightly different effects, compared to the acetate satin samples. A second additional etched layer was added to some of the silk-viscose satin samples. These samples were initially etched and then printed with the thermochromic dye and finally etched again onto the printed layer. Etching with a printed layer applied between two etched layers demanded an extremely high level of precision in order to match the patterns due to limitations in how the samples may be mounted in the laser instrument. Additionally, the layer that had been etched, prior to being printed, with too high an intensity and/or when scan lines were

too close to one another (although differing with particular substrate qualities) tended to break in the etched area when pressure was applied during printing. The most successful samples were those that had been etched more lightly on the surface and not through the fabric. These lightly etched surfaces provided a structure that was sufficient to create the aesthetically interesting effect in the dynamic imageries.



Figures 5.24-5.29 The change within the etched imagery of a silk-viscose sample etched both prior and after the printed thermochromic layer, due to sunlight activation. The change is displayed in the right side of each Figure whereas the left side of the Figure is left unchanged for improved comparison of the change within the sample. The sample demonstrates not only the change from the inactive colour state (magenta) to the active (blue), but also the change in the imagery from the thin lined wing pattern when inactive (Figure 5.24) to the more solid wing pattern when active (Figure 5.29). (Photography: Film & Bildstudion AB)

The part of the pattern that was etched after application of the printed layer was distinctive when the silk-viscose satin samples were observed towards a background that was only weakly illuminated (Figure 5.24). However, the part of the pattern that was etched prior to applying the printed layer was not visible at this stage. This layer became

visible as the back-illumination became stronger. Both etched layers were then visible, as long as the sample was back-illuminated and the dye had not yet moved towards the heated, active colour state (Figures 5.26-5.27). The layer etched after the printed layer became less noticeable as the thermochromic dye moved towards the activated colour state (Figures 5.28-5.29). The layer that was etched prior to the print was still visible. This resulted in several changes within the design, not only in colour, as in the example where the magenta moved towards blue, but also in the imagery as exemplified with the thin lined wing pattern (Figure 5.24) moving towards the more solid wing pattern (Figure 5.29). This feature has previously proved quite difficult to achieve. As stated in section 2.1.5, it has previously involved high-technology solutions, for example, working with incorporated technology such as imagery shaped electrical heating mechanisms, which, amongst other factors, present a high demand on energy consumption.

CD-ROM, Film 5 visualises the changes within the design in terms of the effects of the thermochromism and the etched imagery. The sample, mounted indoors onto a windowpane (set-up A), is printed with light purple that moves towards light blue as the thermochromic dye, with activation temperature 30°C, is activated.

5.4.5 *Laser-cut results*

This section presents the work carried out using laser cutting. The laser-cut investigation, based on around 100 laser-cut samples, as with the laser-etch investigation, aimed to establish appropriate instrument settings, which could create a fabric structure that allowed more sunlight to pass through, as defined in Q5, section 1.3. The same materials were also used. Two main types of structures were created. The first type of structure, involving 80 samples, created successfully on the selected fabrics, involved imageries based on pattern elements that were cut out completely, as exemplified in Figures 5.30-5.31. The main issue to overcome in creating this first type of structure was finding the instrument settings that worked well both with the chosen design and the fabric material. If the settings were underplayed, the shape was not completely cut out, and if the settings created too much heat the material appeared to partly re-seal the path that had been cut. An increase in the maximum power setting, created a deeper cut. However, this required to be balanced in relation to the set velocity setting (beam speed). Different materials needed different maximum power settings. The size and shape of cut outs required careful adjustment of the velocity setting.



Figure 5.30 (left) Examples of the laser cut silk-viscose velvet samples, mounted on a windowpane. Figure 5.31 (right) Part of the shadow cast by the sample on the white wall in set-up C.

The second type of structure, involving 20 samples, involved imageries consisting of elements of laser-cut patterns that were still attached to the fabric (see examples in Figures 5.32-5.33). These designs displayed an expression that in a way resembled the etched surfaces, although the laser-cut imagery consisted of much freer line motifs, rather than shapes created by a lined structure. A more shallow depth of cut (using a lower maximum power setting) resulted in an expression with ‘spots’ and light lines of light within both the surface of the textile and the light and shadow imagery, when the fabric was back-illuminated (see Figure 5.53-5.54). This second type of structure was successfully created on the two satin fabrics, whereas the velvet was not successful in this respect.



Figures 5.32 (left) Sample with laser-cut line structures (the second type of investigated laser cut structures). Figure 5.33 (centre) Close-up of the created light imagery on non-printed sample, etched with structure type two, when the sunlight is shining through the sample. Figure 5.34 (right) Part of the shadow cast by the sample in Figure 5.32.

None of the laser-cut structures of either type showed any issues when combined with printed thermochromic dyes. The lined imagery created by the laser beam in the

second type of the structure, as for the laser-etched samples, became more visible when the laser treatment was carried out after printing, compared to before printing, as discussed in section 5.4.4. It is obvious that the sunlight transmission would be most effective (probably 100%T in the area of the cut outs) with the first structural type of laser-cut patterns. The increase in light transmittance (%T), compared with the untreated substrate, of the second type of laser-cut structure, however, was similar in terms of the effect of laser-etching, with an increase of around 5%T, as discussed in section 5.4.2. The laser-cut structures demonstrated a shift of the focal point similar to the laser etched patterns when the weather conditions altered between sunny and cloudy sky as discussed in section 5.4.3. The light and shadow patterns created by the first type of laser-cut structure, using observation set-up C (see section 3.7.2 and Graphic 5.1) provided similar results to the equivalent observations of the devoré-printed structures as discussed in section 5.3.1, but without the two-shaded shadow. In contrast, the results of the observations of the second type of the laser-cut structure were similar to those from the equivalent observations of the laser-etch light and shadow patterns as discussed in section 5.4.3.

5.4.6 *Conclusions of the investigation of the samples created through laser technology*

The analysis of the observations with the laser-treated materials demonstrated technical compatibility with the printed thermochromic dyes. The lightly laser-etched structures had the potential to create aesthetically-interesting dynamic imageries when combined with thermochromic dyes. There was substantially increased light transmittance (%T) in the first type of laser-cut structure (design elements cut out altogether). A smaller increase in the light transmittance was provided by designs created with laser-etch structures based on completely etched-through straight lines as well as with the second type of laser-cut structure.

5.5 Combining the laser techniques, devoré print and printed thermochromic dyes

This section presents an investigation into the suitability of combining one or more of the four techniques investigated (laser-etch, laser-cut, devoré print as well as printed thermochromic dyes) within a single sample. A variety of samples with combinations of the four techniques were prepared to explore the potential of combining these techniques in the same design. Around 30 printed samples were produced with different combinations of lightly laser-etched patterns with the two types of laser-cut structures as well as the devoré print. The lightly laser-etched structures were included in view of their

ability to create the aesthetically-interesting dynamic imagery effects. The two types of laser-cut structure as well as the devoré-printed structures were included to provide variation in the light transmittance values (%T). The samples were printed using thermochromic dye variations using the magenta and purple set colours, with activation temperatures of 27, 31 and 47°C. The substrates used in these tests were a selection of the most suitable materials, in relation to the techniques used, based on the conclusions from prior investigations presented in individual sections of this chapter.

The two versions of laser techniques were highly compatible, as similar techniques using the same instrument. However, it was found to be easiest to etch prior to cutting. The same principle applied when devoré print was combined with laser cut structures, due to the advantage of having a stable (uncut) fabric during the removal of the burned out fibres in the devoré process. The least successful approaches were when devoré-print was combined with the laser-etched structures. It was found that the main part of the samples tended to break easily within the etched area when the burned out fibres from the devoré process were removed. Additional issues that needed to be resolved arose from a degree of fabric shrinking during the devoré process to ensure that the laser treated imagery layers, applied after the devoré layer, still fitted into the design.



Figures 5.35 (left) Detail of a silk-viscose velvet sample that has been laser etched (the linear part of the imagery) as well as laser-cut (the larger cut-outs). The etched velvet surface has provided an expression of a golden colour. Figure 5.36 (centre left) Silk-viscose satin sample printed with the magenta coloured thermochromic hue prior to being laser etched as well as laser cut with the second structural type. Figure 5.37 (centre right) Silk-viscose velvet sample printed with thermochromic dyes as well as yellow permanent puff pigment, after being devoré-printed but prior to being laser-cut. The thermochromic dye in the sample is in its active state (the blue colour), due to the heat from the sunlight in set-up C. Figure 5.38 (right) The projected shadow from sample Figure 5.37 The light grey areas are created due to the devoré-printed areas and the bright light imagery due to the laser-cut elements.



Figures 5.39 (left) Silk-viscose satin mounted in set-up C with the projected shadow on the white angled wall. The sample is printed with thermochromic dyes after being devoré-printed but prior to being laser-cut. The thermochromic dye in the sample is in its active state (the blue colour), due to the heat from the sunlight. Figure 5.40 (right) Close-up on the two-shaded projected shadow. The light grey areas are created due to the devoré-printed areas and the bright light imagery due to the laser-cut elements.

5.6 The effect of laser-cut materials in the sun-screening textile on the relationship between the position of the sun and the light and shadow imageries created: A collaboration

This section presents the work that resulted in the definition of the following key variables: movement of position of imagery, direction of movement within imagery, as well as composition. These variables were defined with the aim to provide textile printmaker practitioners with information that should be considered when creating textile designs that incorporate projected sunlight, so that he/she can provide a more controlled design outcome of the projected light and shadow imageries on the incident surfaces. As discussed in sections 5.1-5.5, some of the light translucent imageries incorporated in the sun-screening textiles (defined as ‘sails’ within this chapter), in combination with sunlight, had the ability to create interesting light and shadow imageries displayed on the incident surfaces in indoor observation set-up C (see section 3.7.2 and Graphic 5.1). An in-depth investigation of the relationship between three-dimensional spaces (the physical space) and the projected light and shadow imageries was carried out in a collaborative project with Barbara Jansen, PhD student in the Swedish School of Textiles, Borås University, Sweden, providing crossovers that led to interesting synergies of input and ideas between the two projects.

This collaborative investigation, as defined in section 3.9, was carried out within a set scenario of an existing street within Seville, Spain. The collaborative conceptual scenario related to the high temperatures (above 40°C) that are normally reached in

Spain during daytime in the summer months (see temperature curves for Seville, Appendix D). The study was constructed around a design application with laser-cut sun sails in the street, which created projected light and shadow imageries that could be controlled through design. Additionally, the design application aimed to create shading from the sun, as well as harvesting solar energy through printed solar cells. The collaborative process was divided into two parts. Firstly, the movement of the projected light and shadow imagery was investigated in relation to the laser-cut design on the sun-screening sail. Secondly, an investigation was carried out, outlined within the conceptual street scenario of Seville, to assess the methods defined within the first part. The investigations were conducted using a 1:20 scale model, which was a simplification of the street in Seville, using an artificial sun, as described in set-ups D and E in section 3.7.4. The investigation was carried out with the use of paper to simulate the sun-screening textiles. In previous laser investigations, see section 5.4, with textile materials it had proved to be time consuming as regards finding appropriate instrument settings for each textile material as well as in creating successful designs. Some initial laser cutting tests, using paper, demonstrated that this was a material to which the laser-technology could be easily applied. Therefore, paper was chosen as an appropriate substitute for this collaborative conceptual investigation, which aimed to explore a substantial number of laser-cut designs. The paper was considered suitable to simulate the intended translucency considered since textile materials would scale incorrectly within the model, due to their thickness. Thicker black paper was used to symbolize non-translucent areas based on solar cells in the conceptual scenario, as defined in section 3.9. A thinner white semi-translucent paper simulated the textile materials. Colour was not a particular focus of this collaborative project.

5.6.1 *Definition of the shapes of the laser-cut structures*

This section contains a presentation of the experimental work and the analysis carried out with the laser-cut imageries and elements, which was the basis for the definition of the key variables. The examples and photographs presented are a selected extract of the work produced, and are presented to aid analysis. An investigation of the laser-cut shapes was conducted, in the first part of the collaborative project, whereby all the chosen designs were cut using both the black and the white paper. Over 200 ordered compositions and loose elements were laser-cut and tested within the collaborative project. The shapes were laser-cut using the default instrument settings for paper (see Table 5.1).

Table 5.1 The instrument settings for laser cutting paper.

Material	Setting for the laser-cut papers			
	Velocity	Min power	Max power	Beam height
Paper (default setting)*	15.0 cm/s	5%	50%	Normal

* Paper is cut on the black bed of the laser-instrument.

The designs were based both on simple geometric shapes (rectangles and circles) and on organic shapes with higher levels of complexity (see Figure 5.41 for examples). The geometric designs were chosen in order to focus on how the shapes would be altered through the cycles (24-hourly and yearly) of the sun in terms of the projected light and shadow imagery created. Circles were chosen for their symmetrical shape and rectangles, due to their clear directional shape. The organic shapes were based on the circle, but morphed into clustered curvilinear and biomorphic shapes. The centre of the shape was moved towards one of the sides, creating a direction within the elements.

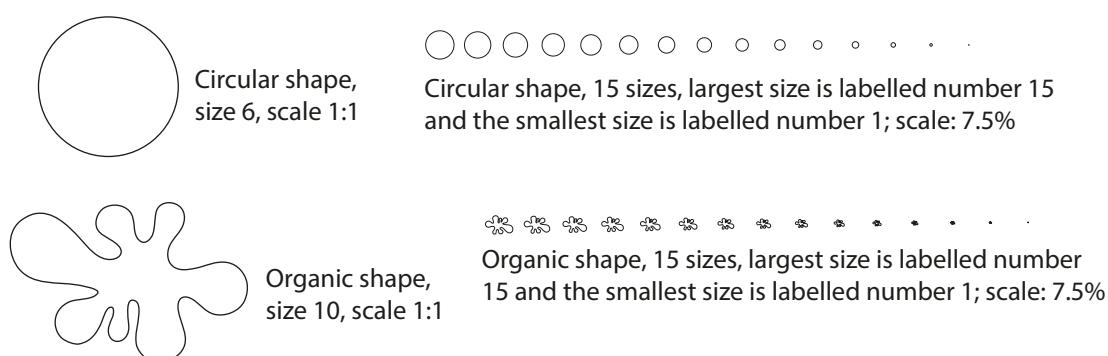


Figure 5.41 Examples of the laser cut organic and geometric shapes and imageries.

The final organic shape was then, additionally, morphed into fifteen different shapes where the last one was a perfect circle (see Figure 5.42). The morphed shapes were used to investigate when the light and shadow imagery, derived from the organically-shaped laser-cut element, would be perceived either as more circular or as retaining an organic shape.

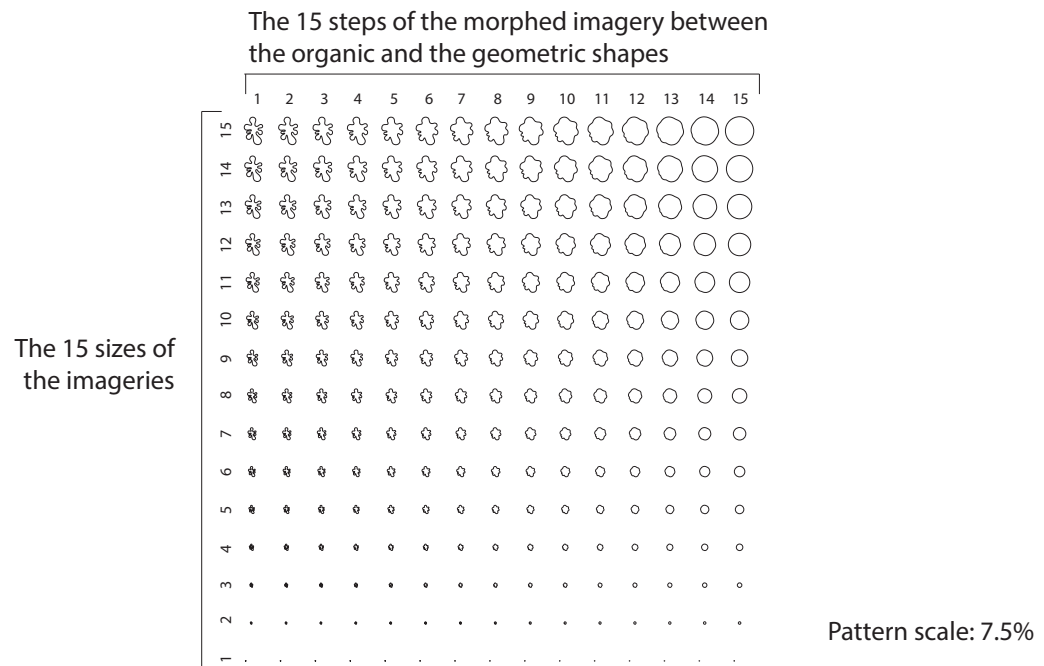


Figure 5.42 The steps of the laser cut imagery of the morphed organic and geometric shapes.

Two additional motifs were investigated including series of either rectangles, changing towards lines, or circles (see Figure 5.43).

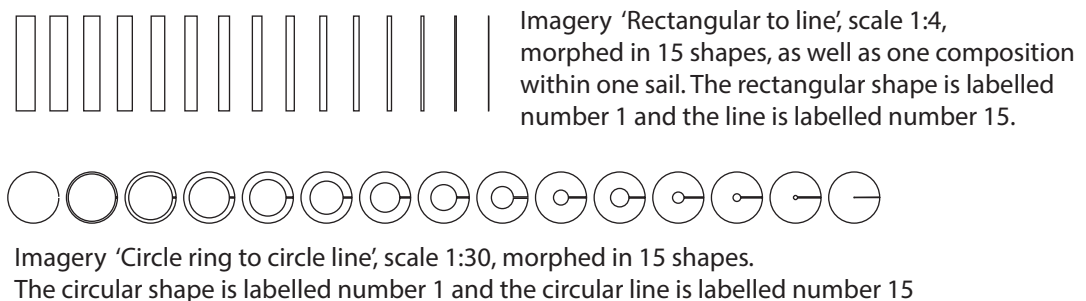


Figure 5.43 The steps in the laser cut imagery that is morphed between a solid and a linear shape.

The series of rectangles becoming lines alters from rectangular to a thin line over fifteen steps and the circular motif starts with a filled circle proceeding to a thin wireframe circle, also over fifteen steps. All designs were produced in fifteen scaled versions. The longest dimension of the largest sized element would have measured 1m in full scale (5cm in the model) and of the smallest sized element 2cm in full scale and 1mm in the model.

The lamps in observation set-ups D and E, as defined in Graphics 5.2-5.3, were placed so as to simulate the position of the sun at noon since that was observed as the time of day when the projected light and shadow imagery was least distorted. The two

sets of designs used in the sun-screening sail (ordered composition and loose elements, see Figures 5.44-5.47 as well as Figures 5.51-5.55) were dealt with slightly differently during the experiments.

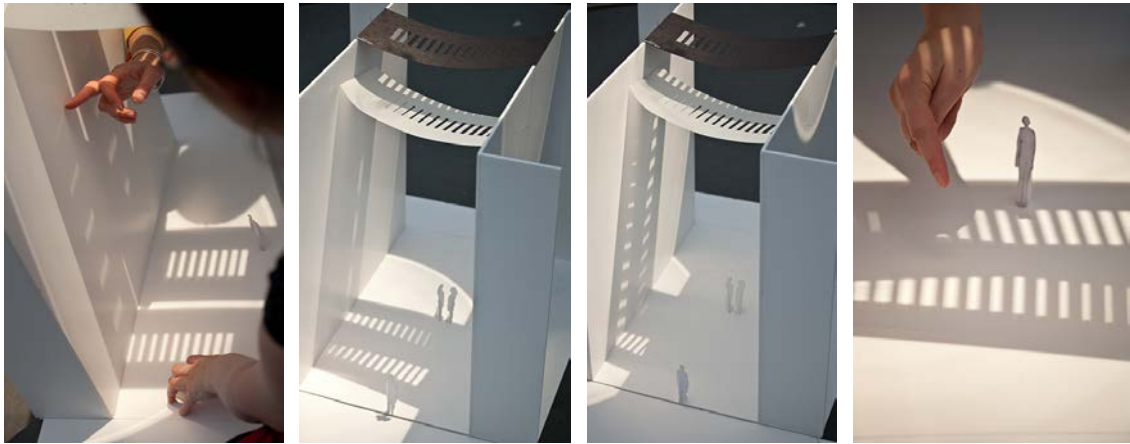


Figure 5.44-5.47 Examples of light and shadow imageries created using the set composition ‘Rectangular to line’ in different constellations, using set-up E. Figure 5.44 Example of set-up with two parallel sails, facing the same direction within the laser-cut imagery. Figure 5.45-5.46 Example of set-up where the white sail is placed lower and angled in, under the black sail as well as with an opposing direction within the laser-cut imagery compared to the black sail. (Photography: Imaginara)

The ordered compositions were mainly, due to their pre-defined static expression, pinned across the street within the model either alone as a single sail or together with two or three sails to make an additional composition (see Figures 5.44-5.47). However if more than one sail was used in the model, the placement of the screening sails was varied. The sails were placed either at the same or at different heights, parallel to or at an angle to each other, and combined next to each other in different compositions (see Figures 5.44-5.45). Additionally, the sails were placed either with their laser-cut designs facing the same direction or opposite to each other (see Figures 5.44-5.45).

The investigation of the loose elements, however, required the involvement of a more interesting and intuitive creative process. The loose elements were moved around freely on top of transparent acetate film that was placed across the street in the model, as illustrated in Figures 5.48-5.50.



Figure 5.48-5.50 The loose elements were moved around freely on top of transparent acetate film that was placed across the street in the model. (Photography: Imaginara)

A composition that was considered to have an appealing expression was documented photographically before the loose elements were re-organised into a new composition. This process provided the possibility to sketch motifs both as seen on the sun-screening textile and as observed on the incident surfaces within the model (see examples in Figures 5.51-5.55).

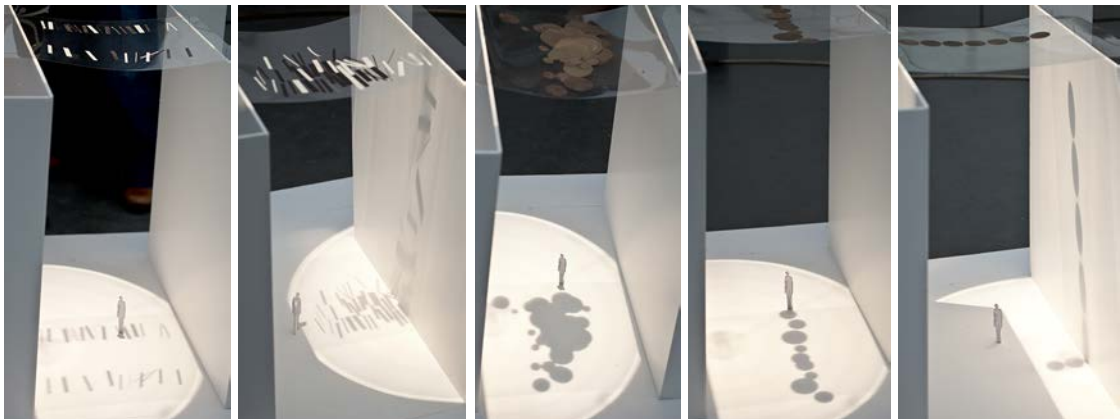


Figure 5.51-5.55 Examples of compositions created using the loose elements, using set-up E. (Photography: Imaginara)

The pattern could be easily altered and rearranged until an appealing expression was created that had potential both as a two-dimensional design on the sun-screening textile and as projected ‘three-dimensional’ imagery on the walls and floor. The process provides a tool for textile practitioners when creating textile designs that provide moving light and shadow imageries due to the presence of sunlight. Within this collaborative project, this method could be used either in set-up D (a model and a LED-lamp) or set-up E (a model and a daylight laboratory) (see Graphics 5.2-5.3). The latter would most likely provide more precise indications of the actual light and shadow

imagery at full scale. However both set-ups provided essential information for the collaborative design process. Set-up D proved effective at an initial stage of the creative process, whereas a substantial number of designs needed to be chosen for the more in-depth and time-consuming investigations using set-up E.

5.6.2 *Definition of the directional movement of as well as within the light and shadow imagery*

This section presents the definition of the key variables: movement of position of imagery, direction of movement within imagery as well as composition. The street and walls within the model, created on the basis of the conceptual scenario as defined in section 3.9, on to which the light and shadow imagery was projected, were divided into five zones (see Figure 5.56) for the purposes of analysis. Each zone corresponded to a period of the sun's path in set-up E (in the daylight laboratory).

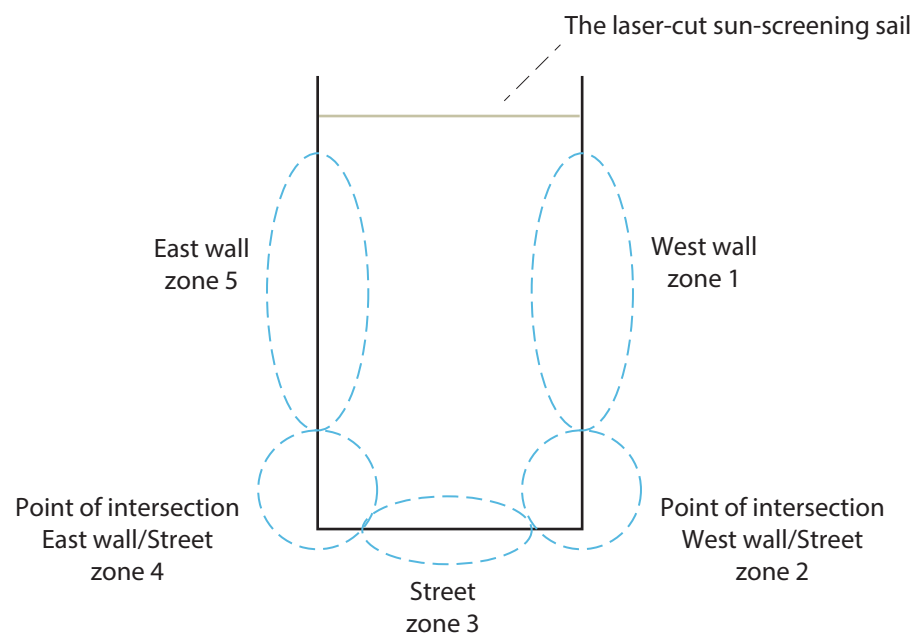


Figure 5.56 The subdivision of the five zones in the street and on the walls of the model onto which the light and shadow imagery was projected, during the sunlit hours of the sun's path.

An enhanced understanding of the effect on the aesthetic outcome of the shape of the projected light and shadow imageries can be obtained by studying *how* the cycle of movement of 'the position of the light and shadow imagery' (key variable 1) changes the shape of the projected light and shadow imageries, in relation to cycles of sunlight (both daily and yearly). Therefore, continuous sun paths were studied in order to analyse the direction and flow of the movement of the light and shadow imagery. The

light and shadow imagery provided, as expected, a clear movement *of the position of the imagery* towards north seen over the year from June to December and then back again (observed from the point located under the laser-cut sun-screening sail, as illustrated in Figure 5.57). The red arrow, in Figure 5.57, illustrates the position of the path of the light and shadow imagery on June 21st (the longest day).

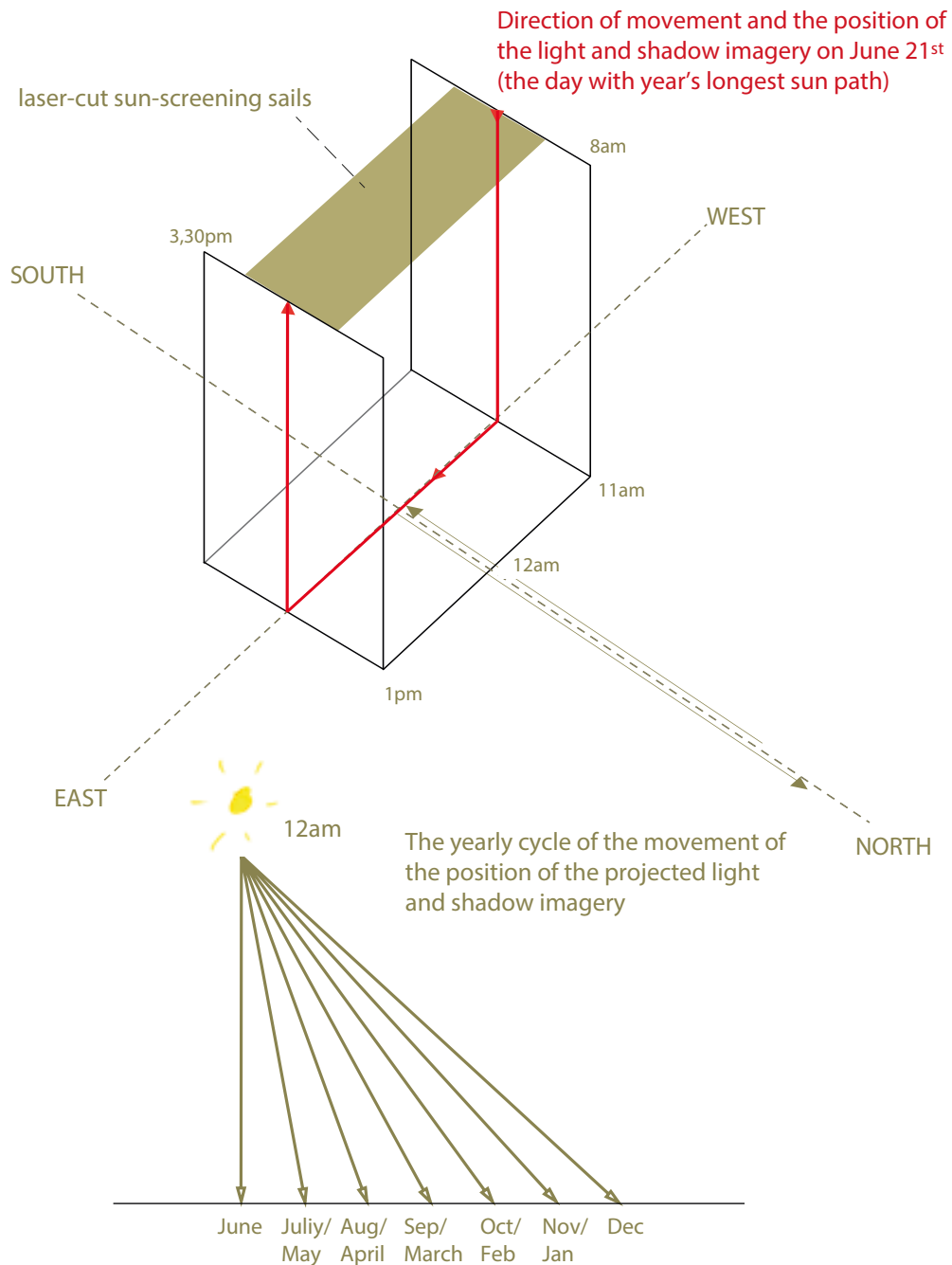
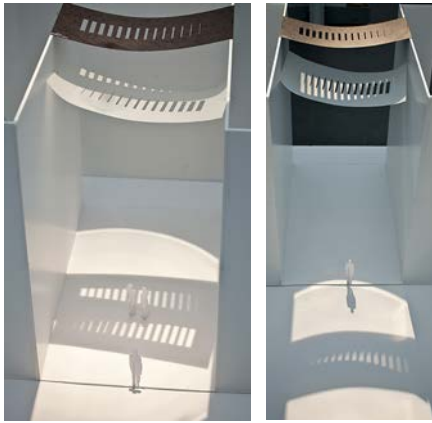


Figure 5.57 The directional movement of the position of the light and shadow imagery, seen over the yearly and daily cycle.

The degree of distortion of the light and shadow imagery, therefore, in relation to the laser-cut design on the sail, provided a transformation of the pattern extended more towards north, which resulted in a quite different visual expression when the months closer to June were compared with the months closer to December (see Figures 5.58-5.59).



Figures 5.58-5.59 The placement of the light and shadow imagery at noon in June-July (left) and December-January (right). Not only the position of the light and shadow imagery (see placement of the imagery in relation to the figure in the model) but also the outlook (the shape) of the projected imagery differs between the two timeframes. (Photography: Imaginara)

The laboratory work carried out within this thesis, demonstrated that some imageries that had been considered interesting during the summer months provided a duller expression during the winter months, whereas others provided a more interesting result during the full year. These results thus lead to the recommendation that the designer should investigate the full cycle of the year of the light and shadow imagery, for example by simulation within a daylight laboratory.

The *movement of the position of the projected imagery* was, as expected, also related to the sunlit hours of the daily cycle. The position of the light and shadow imagery followed a west-east path through the five zones, as illustrated by the red arrow and the time given, using June 21st as an example, in Figure 5.57.

However, the investigations of the path of the projected light and shadow imageries not only simulated the cycle of the sun's yearly and 24-hour cycles, but also demonstrated a *movement within the imagery* (key variable 2) from the design. The projected light and shadow imagery, as illustrated for the design 'rectangle to line' in Figure 5.60, provided a clear directional movement *within the composition* (key variable 3) of the elements, whereby the imagery was observed to move along the walls and floor of the model (following the sun's path) in set-up E. The red arrow, in Figure 5.60, symbolizes the

direction of the sun's path during the sunlit hours. The position of the actual laser-cut paper sails are illustrated as light brown and the projected light and shadow imagery in black.

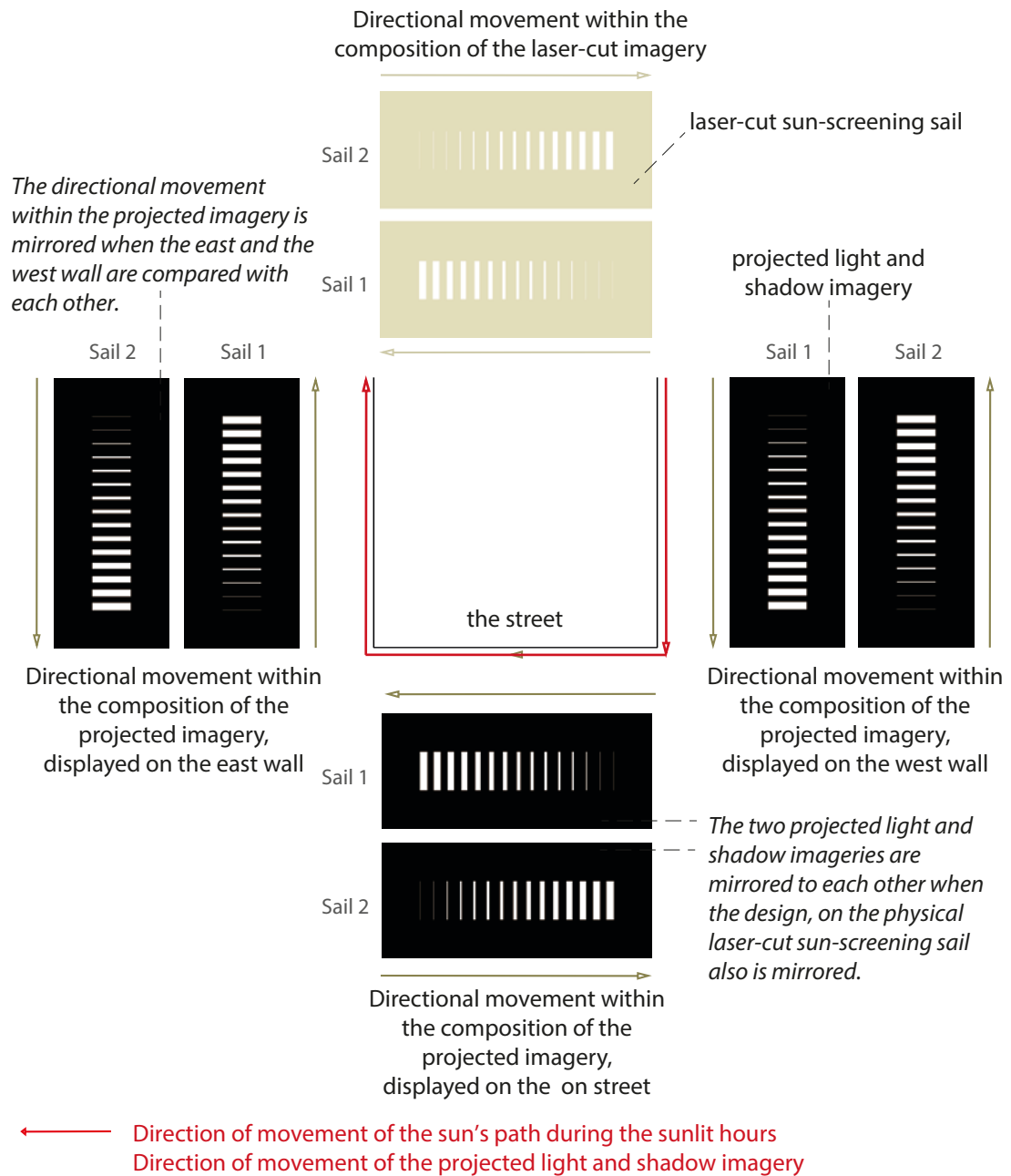
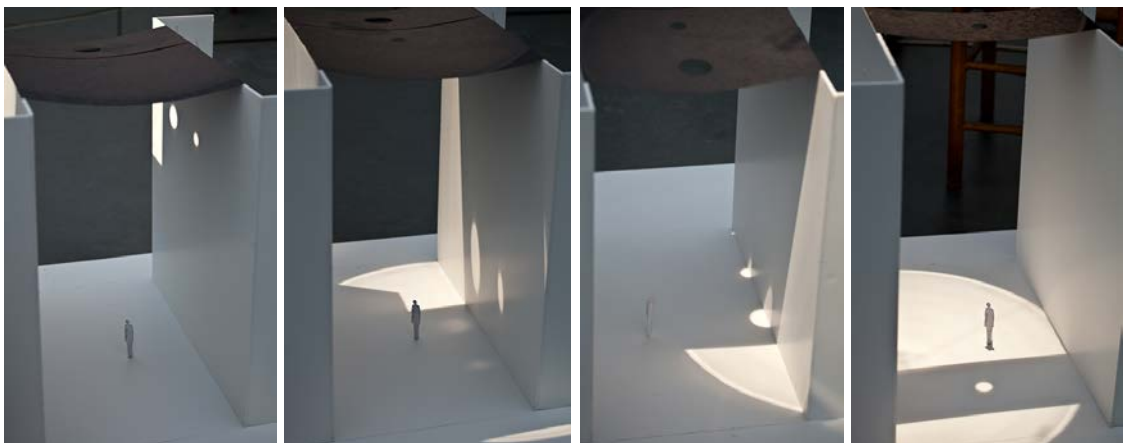


Figure 5.60 The directional movement within the light and shadow imagery. Illustrated with the 'line to rectangle' design.

The projected light and shadow imagery of the sails, illustrated in black and numbered as 1 in Figure 5.60, provided a directional movement downwards along the west wall and upwards along the east wall. The corresponding imagery of the second sail, in black, numbered as 2, demonstrated the reverse effect whereby the design on the sun-screening sails was mirrored (see the black sails, 1 and 2, in Figure 5.60). The conclusion

from this aspect of the investigation was that the directional movement within the composition of the design on the laser-cut sail was governed by the placement of the sail. Furthermore, the directional movement of the composition was mirrored when the projected imageries of the east and west walls of the model were compared (see the two black sails numbered 1 or 2, next to the walls in Figure 5.60). An additional conclusion was therefore that the directional movement within the composition was related to which zone the imagery was projected onto (in turn determined by the time of day).

The non-directional elements, i.e., the laser-cut circles (both ordered compositions and loose circular shapes) created light and shadow imageries during the sun's path which clearly alternated between ellipses (directional shapes) and circles (non-directional shapes) (see Figures 5.61-5.64). Additionally, the projected light and shadow circles altered from appearing droplet-like (uni-directional), Figure 5.63, to elliptical (bi-directional) Figure 5.62. The conclusion from this aspect of the investigation was that the directional movement within the design is determined by the shape of the laser-cut elements.



Figures 5.61-5.64 Two sun sails (Figs. 5.61-5.63, only one in Fig. 5.64) with ordered compositions with imageries of a laser-cut circle. Figure 5.61 (left) The projected light imageries demonstrate a slight oval, directional form, parallel, horizontally along the street, when projected on either the west wall in the morning or east wall in the evening. Figure 5.62 (centre left) The projected light imageries demonstrate clearer oval, directional form, vertically, along the side of the facade of the building, when projected on the west wall in the late morning (before noon) or the east wall in the afternoon. Figure 5.63 (centre right) The projected light imageries demonstrate clear droplet-like, uni-directional form, with a direction upwards towards the sky, when the projection targets the break-points between the facades and the street. Figure 5.64 (right) The projected light imageries demonstrate a non-directional, circular form when projected straight below the laser-cut sun sail at noon. (Photography: Imaginara)

This set of experiments demonstrated that the directional movement of the projected light and shadow imagery altered both on a large scale, as a result of the

position of the design, and on a smaller scale, within the design. The former changes were found to relate to the sun's daily and yearly cycles, and the latter to the placement of the sun-screening sail, the time of day and the nature of the elements within the design. These established factors provide a tool to which textile practitioners may relate in creating these types of designs in such a situation.

5.6.3 *Conceptual compositions of light and shadow imageries to evaluate the defined design methods*

This section contextualises key variable 1, *the movement of the position of the projected imagery*, by demonstrating how the position of a design (laser-cut imagery [a] and [b] in Figures 5.66-5.94) within the textile may be used, not only to vary the expression of the projected imageries, but also to create a 'connection' between the actual three-dimensional space as well as hours of effective sun-shading.

The second part of the collaboration focused on the concept of creating sunshade in the conceptual street scenario in Seville, Spain, as defined in section 3.9. The need for shading in the real situation was based on data available for Seville, of the hottest months of the year and the hottest hours of the day (see data and diagram for Seville, June 21st, 2010, Appendix D). This analysis resulted in a focus on the hours between noon and 2pm (corresponding to zones 2 to 4, in Figure 5.65).

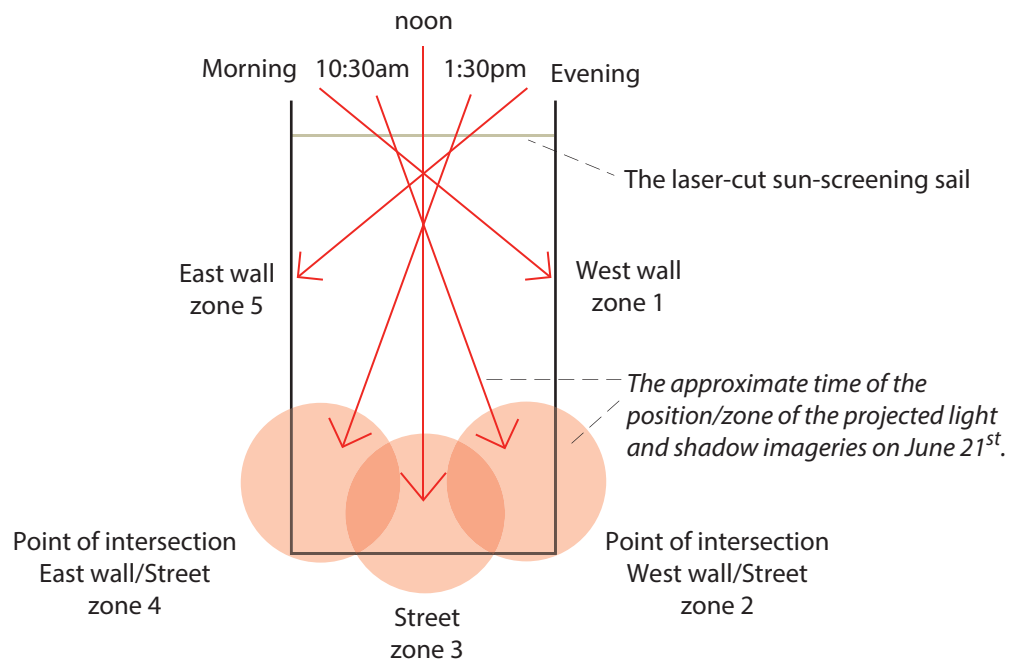


Figure 5.65 The distribution of the sunlight in the conceptual street on June 21st.

The outcomes of the first part of the collaborative study were tested during the course of the design process in the second part. The light and shadow imageries that were created from rectangular laser-cut elements appeared easiest to interpret when all designs were compared using the sun's path on the 21st of June. It was therefore decided that the rectangular shapes would form the foundation of the second part of the collaborative study. A variety of laser-cut compositions of rectangular elements were observed and tested in comparison with the use of a more intuitive method involving free loose laser-cut elements as defined by the collaborating researchers, as explained in section 5.6.1. The two most aesthetically appealing compositions that were also considered to create enough shade in the street within the identified timeframe were selected for a comparative analysis using set-up E, as defined in 3.7.4.



Figures 5.66-5.68 Laser-cut imagery (a), along the street. Figure 5.68 (right) Laser-cut imagery (a) demonstrates an offset of the placement of the projected light imagery at noon, due to the placement of the laser-cut imagery towards the east wall. (Photography: Film & Bildstudion AB)



Figures 5.69-5.71 Laser-cut imagery (b), across the street. Figure 5.71 (right) The projected light and shadow imagery from laser-cut imagery (b) creates an feeling of a 'light bridge' between the east and the west wall, when the projected imagery is positioned centred on the street between the two facades. (Photography: Film & Bildstudion AB)

The first laser-cut imagery (*a*) was designed so that it oriented with a north-south direction: the laser-cut elements on the sun-screening sail were aligned along the street (see Figures 5.66-5.68). The second design (*b*) was oriented in an east-west direction; the laser-cut elements were aligned across the street (see Figures 5.69-5.71). Colours to symbolise the thermochromic dyes that were envisaged for incorporation into the designs as discussed throughout this thesis were simulated by printed colours on paper.



Figures 5.72-5.82 Sun-path of the projected light and shadow imagery created from laser-cut imagery (*a*).
(Photography: Film & Bildstudion AB)



Figures 5.83-5.94 Sun-path of the projected light and shadow imagery created from laser-cut imagery (b).
(Photography: Film & Bildstudion AB)

Animations of the movement of the sunlight and the position of the projections of the light and shadow imageries were created so that key variable 1, the moving imageries due to the two different laser-cut motifs, could be compared. Analysis was then carried out to assess how well the chosen light and shadow imageries, due to the two laser-cut designs, connected to the space within the conceptual street and the people moving inside the street and also to assess the efficiency in providing the intended shade. Visualisations within the model of the street in Seville, Spain of the movement of the two light and shadow imageries (a) and (b) as well as the thermochromic colour change in imagery (a)

on the side of the sun-screening sails facing the street are given in Figures 5.72-5.94 and CD-ROM, Film 6.

The light and shadow imagery in the design (*b*) suggested for use across the street appeared to create a visual bridge that connected the two walls during the time when the imagery was projected in zone 3 (and to some extent zones 2 and 4). This was considered to provide an almost tangible link between the walls, thus creating an interesting aesthetic relation to the physical space within the street (see Figure 5.71).

We are creating a physical bridge between the façades... we feel that those patterns are more interesting. (Analysis of the tests, 2010-03-02)

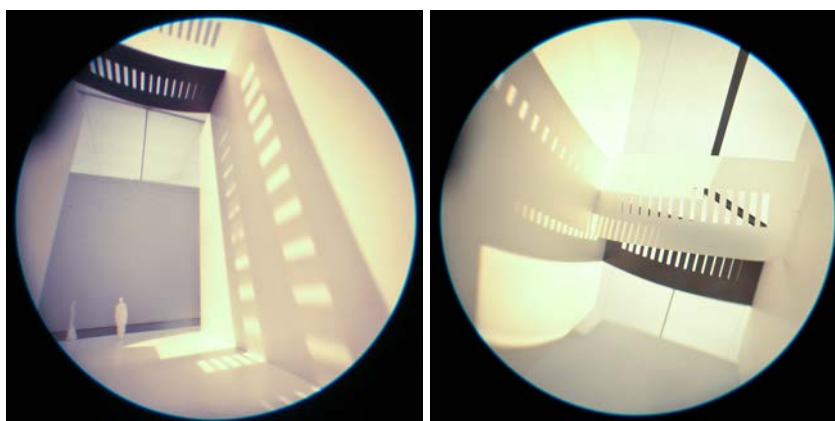
On the other hand, the initial laser-cut imagery (used along the street, *a*) was designed to appear to create an offset in relation to the centre of the street to assess whether this could create more shade during the hottest hours of the day. The light and shadow imagery was projected at noon in zone 3, on the border with zone 4, rather than centred in zone 3 (see Figure 5.68).

Estimations of the time when the sunlight reached the different zones within the study were based on a photographic documentation of the simulated sun path taken in the daylight laboratory (see examples in Figures 5.72-5.94) and the sun position diagram for the latitude and longitude of the street scenario in Seville, Spain (see Figure 3.18). Conceptually, the street was observed to be in full shade at around 1:30pm if the design along the street (*a*) was used and at around 2pm if the design across the street (*b*) was used (see Figures 5.80 and 5.90). The estimated timeframe that the projected light and shadow imagery shaded the street was 2.5h and 3.3h for imagery (*a*) and (*b*) respectively. This conclusion was based on the time it took for the projected imagery to reach zone 5, the east wall, from its position at noon. The street would be slightly less shaded if the design (*a*) was used, during the timeframe that the light and shadow imagery was projected in zone 3 (roughly between 11:45am and 12:15pm). However, the street would still be shaded by the areas between the cut-out elements of the projected light and shadow imagery.

The study and analysis of key variable 1 of the two design alternatives, (*a*) and (*b*), resulted in the conclusion that both designs created connections between the space within the street in the model and the people placed within in it. However the aesthetic outcome of such a connection appeared to vary to a large extent. Furthermore, the analysis resulted in estimations of the time of the movement of the shadow imagery,

which indicated a successful shading scenario, but with a slight variation in the number of hours in shadow.

Additionally, the practitioner has to be aware of factors of scale and viewing angles in using the design methods when creating and sketching imageries in the model. The designer gains a birds-eye perspective, which a viewer in a real full-scale application will not have, because the viewer in the street is normally standing below the actual sun-screening textiles. A small micro camera, as is commonly used within architectural projects, was used successfully within the collaborative project to attempt to simulate the appropriate point of view of a person viewing the sun-screening textile from the street. The camera that was used, for both stills and for animation, was placed inside the model at an average human eye level. The camera was moved around to simulate a person within the model looking around and upwards to the sun-screening textiles (see Figures 5.95-5.96).



Figures 5.95-5.96 Stills using the micro camera to simulate the view from someone standing inside the model in the scenario of a street in Seville. The round format is due to the construction of the camera. (Photography: Imaginara)

5.7 The relationship between projected light and shadow imagery and the dynamic effect of thermochromic dyes activated by sunlight

This section explains how the descriptors of sun-activated thermochromic dyes, which were defined in section 4.4.7, require slight modification when the light and shadow imageries from projected sunlight are defined. As outlined in research question Q5, section 1.3 the aims of this thesis have been addressed by the creation of light and shadow imageries using the design concept based on the use of the sun as an activator for thermochromic dyes printed on sun-screening textiles. It is, as defined in research question Q6, section 1.3, of particular interest that both the light and shadow imageries produced by the textiles and thermochromic imageries printed on the textiles exhibited

dynamic behaviour, as defined in section 2.2.1, whereby patterns appeared and disappeared in response to external stimuli. In both cases the stimuli were linked to interaction of the textile with sunlight. Both may be considered as transforming between active and inactive states. As discussed previously in this thesis, the heat from the sunlight enables a colour change due to activation of printed thermochromic dyes and the sun's illumination causes the projected light and shadow imagery. However, there were differences between these two types of imageries regarding their dynamics. The thermochromic imageries were reversible between inactive and active colour states, defined in chapter 4.4.7 using the descriptor $\{A T B_i(s^{dt}) T A\}$ where A refers to the inactive state, T to the transitional state and $B_i(s^{dt})$ is the active state (B is dependent on the sky conditions s and the number of different motifs i). The light and shadow imageries demonstrated a more complex dynamic behaviour, which is defined by both daily and yearly cycles (see Figure 5.97).

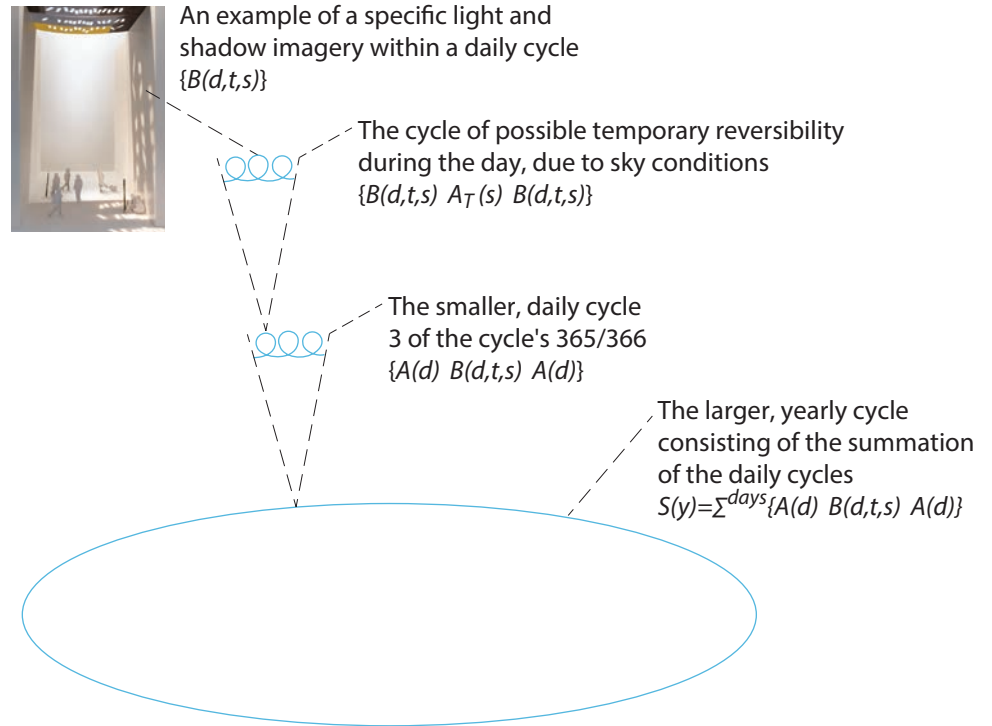


Figure 5.97 Graphic illustrating the cycles of movements of the light and shadow imagery.

The daily cycle involves (see Figure 5.97) the path of the projected light and shadow imagery over a 24 hour period and is defined by $\{A(d) B(d, t, s) A(d)\}$ where A is the inactive state (no visible light and shadow imagery) (dependent on the date, d) and B is the active state (an visible light and shadow imagery) (dependent on the date d , the time of day t and the sky conditions s). The yearly cycle, is defined as $S(y) =$

$\sum^{days}\{A(d) B(d, t, s) A(d)\}$, consisting of a summation of the daily cycles that are created over a year (365 or 366 days depending on whether it is a leap year or not) and is dependent on the specific year y , because of natural variations in sky conditions year by year. Therefore, in contrast to printed thermochromic imageries, projected light and shadow imageries are dynamic in the senses both that they can transition between the inactive state (non-projected imagery) and the active state (a projected imagery) and that they project a pattern on a surface, which changes during the day. Since time is a continuous variable, during the course of a day, the light and shadow imageries form a continuously changing pattern on a surface. For the purpose of analysis, it is suggested that the observer may choose to divide the day into a specific number (N) of equal periods in order to study the projected imagery at any particular time. If the periods of time are small enough, for example a minute, the projected imageries from one minute to the next will be similar.

The specific projected light and shadow imagery $B(d, t, s)$, as illustrated by consecutive images in the cycle of the daily paths $\{A(d) B(d, t, s) A(d)\}$, largely resembles the specific imagery of the preceding or following specific projected light and shadow imagery $\{B(d \pm 1, t, s)\}$. Additionally, the daily and annual cycles are similar from one day $\{A(d \pm 1) B(d \pm 1, t, s) A(d \pm 1)\}$ or year $S(y \pm 1)$ to the next, but might differ when a particular light and shadow imagery $B(d, t, s)$ is compared on different days and times, due to variation in sky conditions (see Figure 5.97).

The two versions of imageries, the printed thermochromic and the projected light and shadow imagery, display similar dynamic characteristics in the presence and absence of sunlight. The temporal pattern of the printed pattern, as defined in sections 4.4.3, is dependent on the sky conditions as regards the beginning and ending of activation and inactivation phases involving the time intervals t_l^{i-a} and t_l^{a-i} that provide colour states t_2^i and t_2^a , as defined in 4.4.2 (see Figure 5.98). However, the temporal pattern of the projected imagery is primarily controlled by the sunrise and sunset times, even though particular sky conditions, for example lightly cloudy or heavily overcast sky, could create variation in the projection of the light and shadow imagery during the daily cycle $\{A(d) B(d, t, s) A(d)\}$. Because of the sky conditions, occasionally, this creates a reversible cycle of imageries $\{B(d, t, s) A_T(s) B(d, t, s)\}$, where $B(d, t, s)$ represents a projected light and shadow imagery and $A_T(s)$ represents a temporary non-projected imagery that is dependent on the sky conditions (see Figure 5.98).

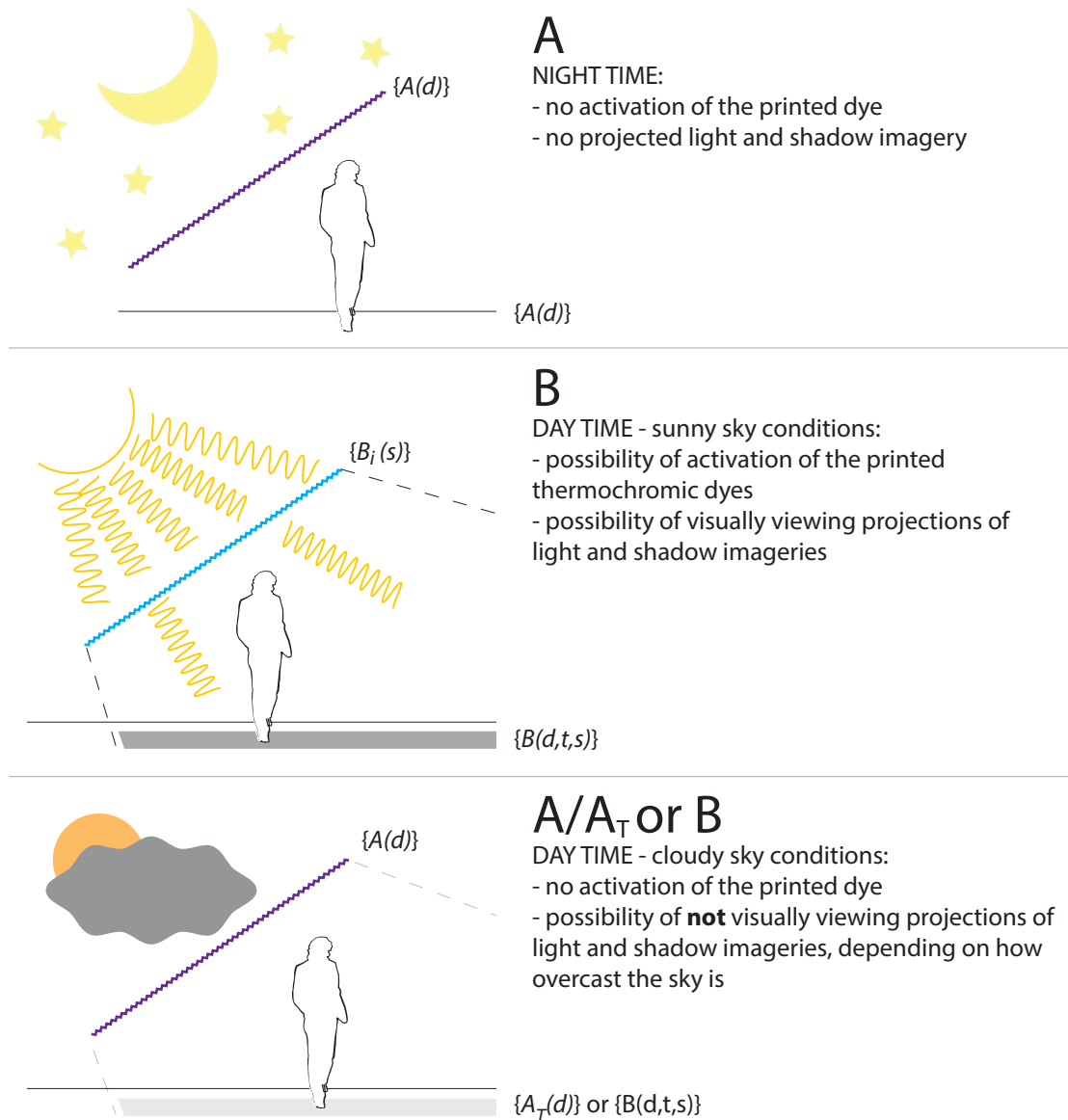


Figure 5.98 Graphic illustrating the temporal patterns of the sun-screening textile printed with thermochromic dyes as well as the projected light and shadow imagery.

The time interval of the projected and the non-projected imageries is, in the case of $\{B(d, t, s) A_T(s) B(d, t, s)\}$, defined by the times t_2^i and t_2^a , where t_2^i represents the times that the imagery may not be visible and t_2^a when it is visible. The observations in sunlight of the printed, light translucent materials (the devoré printed and the laser treated samples, see section 5.3.1) showed synchronisation in the temporal patterns between activation and inactivation phases of the thermochromic imagery and the occasional activation and inactivation phases of the light and shadow imageries (as is displayed in Film 3, part III on the CD-ROM).

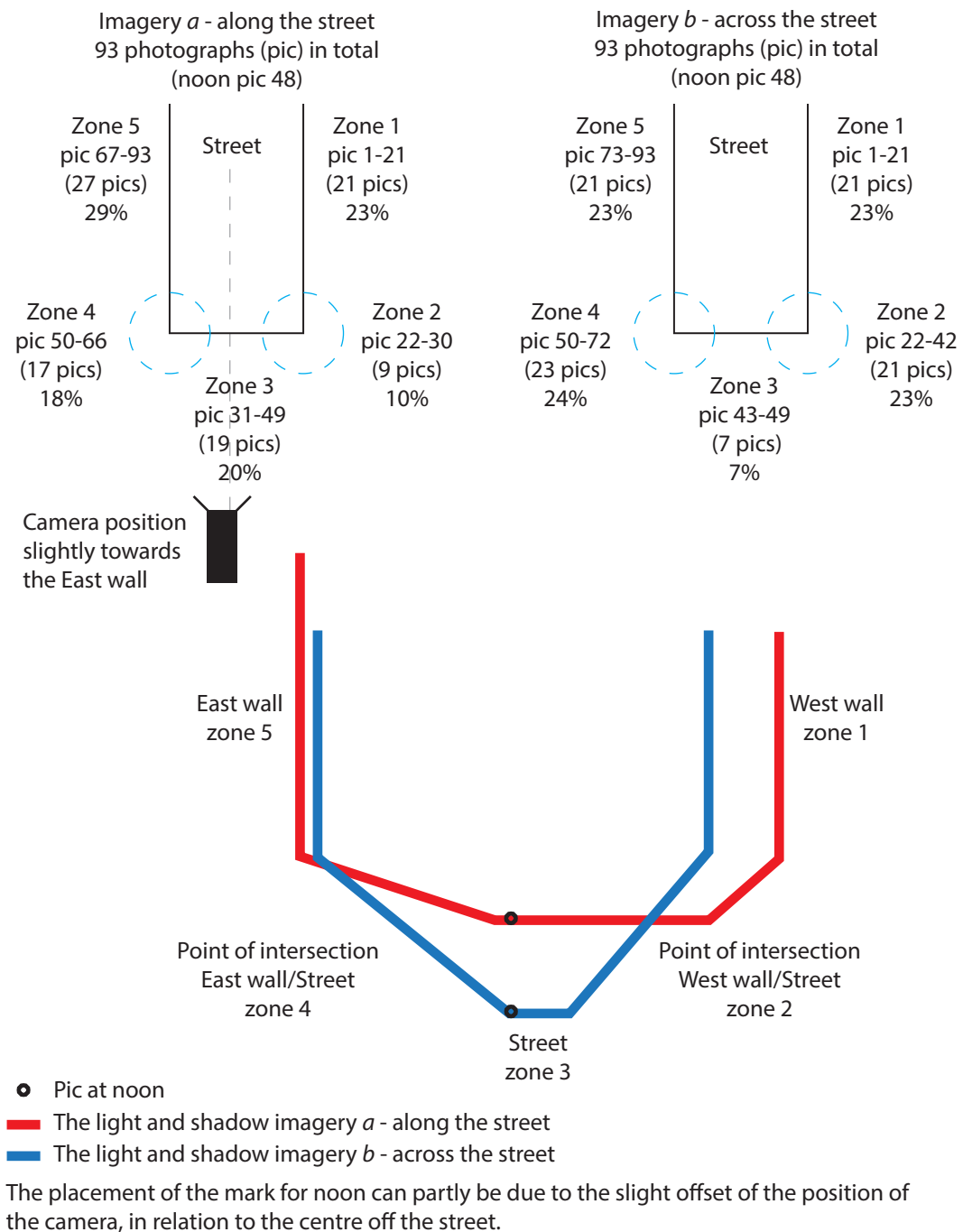


Figure 5.99 Graphical illustration and calculations of the time and tempo of the two light and shadow imageries of the designs, which were compared.

To some extent, the temporal pattern can also be influenced through design choices even though it is controlled mainly by sunlight as a random parameter. The activation in an area of the textile printed with thermochromic dye can be prolonged or shortened in the design by the use of dyes with different activation temperatures, as defined in sections 4.4.2-4.4.3. Approximate calculations of the two examples of light and shadow imageries, from section 5.6.3, were carried out to demonstrate the way that the temporal

pattern of the movement of the projected imagery might also be influenced through design choices. These calculations were, as the calculations in section 5.6.3, based on the photographic documentation of the simulated sun path and the sun diagram for the latitude and longitude of the street scenario in Seville, Spain. The calculations referred to the number of photographs (x) that correlated with each of the five individual zones (z) relative to the total number of photographs (N) taken for each of the two light and shadow designs (a) and (b). The percentage of the imagery, either (a) or (b), projected within each zone was calculated, as illustrated in Figure 5.99, using the equation $\{x_z/N \times 100\}$. Each version of light and shadow imagery was documented by 93 photographs taken at times evenly distributed over the course of the sun's path. The temporal patterns of the movement of the two designs differed depending on zone. Imagery (a) moved quicker through zones 2 and 4, compared to imagery (b), because its design was aligned along the street rather than across it, as illustrated in the red graph in Figure 5.99. In addition, imagery (a) moved faster through the first half of the zones compared with the second half of the zones, due to the offset of the design (see red graph in Figure 5.99). Imagery (b) crossed zone 3 in a shorter timeframe (around 30min), compared to imagery (a), because its design was aligned across the street (see blue graph in Figure 5.99).

5.8 The extended imagery

'The extended imagery', which is defined in this section, consists of 'the physical textile', 'the intermediate zone' and 'the incident surfaces'. The definition was derived on the basis of the experiments and observations concerning the investigation into the potential to design imageries that cover several levels within a three-dimensional space.

In many ways, the process of being a textile designer, broadly focuses on the aesthetics of the surface and the construction of a rather flat material. Traditionally, a textile print design commonly focuses even more specifically on the aesthetics of a flat surface, through the relationship between graphic mark making and the surface of the substrate, compared to other, construction-based techniques such as weave or knit. 'Traditional' textile prints do not necessarily have to exclude a structure that is not flat; there are materials and effect dyes that create, for example, relief structures. However, the result remains quite flat. Of course, artists and textile designers are creating interesting and beautiful three-dimensional textile pieces and/or sculptures alongside the 'flatter' two-dimensional textiles. However, the 'extended imagery', as investigated in this research, aims to underline the possibility to create three-dimensional effects from

the two-dimensional textile fabric, through the use of sunlight (see Figure 5.100). The definition of the ‘extended imagery’ was included in this thesis to demonstrate *how* textile designers more actively can address, not only functions, but also extended aesthetics by working with all or parts of the three levels of the extended imagery.

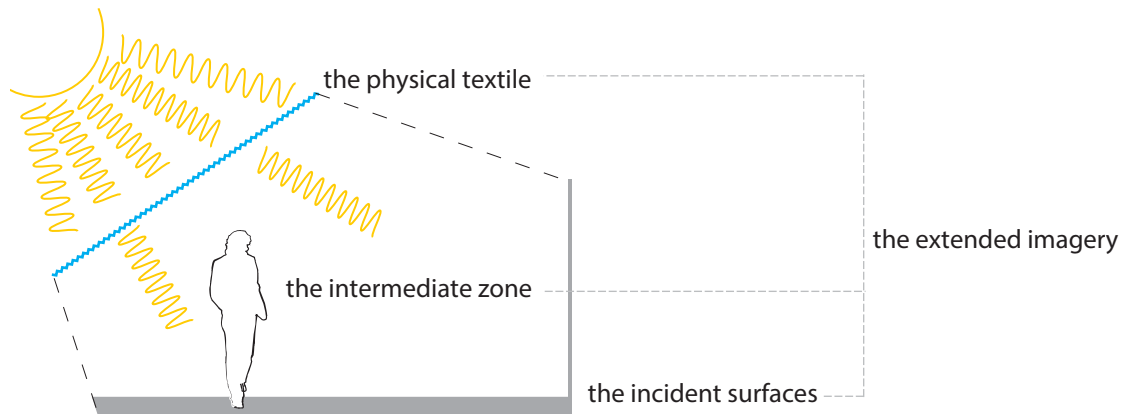


Figure 5.100 Illustration of the different sub-levels of the extended imagery: the physical textile, the intermediate zone and the incident surfaces.

The level defined as *the physical textile*, is the actual physical textile. For example, it can be intended as a sunscreen, as is the focus within this thesis, whose function is to partly or fully block out sunlight. However, the textile does not necessarily have that function. The core of the concept of the ‘extended imagery’ is to utilize the presence of sunlight in relation to the design of the textile. Design decisions concerning the expression and aesthetics of the textile (shape, colour, material, imageries etc.) on the level of ‘the physical textile’ will, of course, have an impact on the viewer. The key factor is that the design of the physical textile will, additionally to its own aesthetic surface, also impact greatly on the light quality of the ‘intermediate zone’ as well as the aesthetics of the projected light and shadow imagery on the ‘incident surfaces’. *The intermediate zone* is defined as the space through which the sunlight travels between the textile and the surfaces. The intermediate zone is the space that humans occupy. *The incident surfaces* are defined as the surfaces (walls, floors or other objects) that the projected light and shadow imagery is displayed on. The intermediate zone represents the second level that the textile printmaker practitioner can work with. The incident surfaces create the third level that the textile printmaker practitioner can work with.

The design of the physical textile influences the quality and amount of light in the spaces that exist between the textile and the ground as well as other surfaces. The light quality is important to those individuals that are in, or move through, this area. The illuminated situation in the intermediate zone might be designed to meet functional requirements and spatial awareness in particular situations. For example, enough sunlight might need to be screened to create a feeling of being cool enough whilst not being blinded by the light, as stated in section 2.3, or to highlight certain objects in the room. However, light can also contribute to evoking emotional experiences. For example, enough sunlight might need to pass through the textile to create a particular intended emotional experience, such as when light is scattered by water droplets in early morning mist or to create more strongly lit areas (almost as if an illuminating spotlight). For example, control may be exerted through the design of the degree of light translucency in the sun-screening textile, e.g., through the shape of imageries or material choices of the physical textile, as illustrated in section 5.3-5.4 through the laser and/or devoré treated structures. Designing the aesthetic expression of the intermediate zone may result in textile designers having to expand their thinking more towards the vocabulary used by lighting designers. The way that lighting designers have to understand the use and effect of different lamp fixtures and the behaviour of the natural light to create, shape and position the light experience as well as tune light levels, could be used by textile designers as a metaphor when working with the aesthetic effects that the physical textile may bring to the ambience in the intermediate zone.

Also, the design of 'the physical textile' influences the shape of the light and shadow imagery that is projected onto the different incident surfaces. The projected light and shadow imagery can, as with the other two levels, be designed to meet functional needs within the space. However, as with the other levels, it can also be designed to deliver aesthetic possibilities, in the sense of the spatially and temporally dynamic imageries. The presence of sunlight creates the possibility of designing an imagery extension of the design of the physical textile, in terms of shape as well as pattern, if the textile design contains translucent motifs. An example of this in this thesis was illustrated by the design of the projected light and shadow imageries shown in Figures 5.72-5.94, section 5.6.3. This provides an example of designing for the aesthetic expression of incident surfaces leading the textile designer to expand their 'vocabulary thinking'. For example, this could mean studying how light designers and set

designers in a theatre use spotlights and gobos⁸ to create shadow imageries within a theatre play to communicate with both the environment as well as the human bodies on the stage.

Other contributing factors that will influence the viewer's aesthetic expressions of the three levels are, for example, the sun's position (time of day, date and geographical position) as well as other artificial light sources that may be present.

⁸ A gobo is a physical stencil often used within the theatre, The stencil is slotted inside, or placed in front of, a lighting source, to create an projected imagery, for example.

Chapter 6 The sun as an indirect activator for textiles printed with thermochromic dyes

This chapter (part III) investigates the potential for using sunlight to indirectly activate textiles printed with thermochromic dyes, as defined in research question Q2, section 1.3. In addition, there is an investigation into the relationship between thermochromic dyes and indirect solar energy during activation and deactivation of the dyes. Indirect activation is defined as activation of the thermochromic dyes using electrical heating mechanisms that are powered by solar cells (photovoltaic), thus using the sun as a renewable energy source to power the solar cells. In principle, this gives the designer the potential to use a power supply that is not only more sustainable, but also controllable. This high-technology solution was investigated as a future possible activation method for applications. There have been several design concepts published in the literature that use electronics to activate the thermochromics, but they are not powered by renewable energy solutions. Some examples of applications in the literature have been presented in section 2.1.4, *Thermochromic dyes in design*.

The main contribution of this chapter is the proof of the concept that photovoltaics may be used successfully as an energy source to power the heaters to activate thermochromic dyes within textiles (section 6.1). The possible applications that the research described in this chapter addresses are primarily sun-screening textiles, defined in 3.2.2, as discussed previously in the thesis, where sunlight shines directly on the textile. However the indirect activation approach could also apply to textiles that are not exposed to direct sunlight. The indirect activation method applies either when solar cells are integrated in the textile or when the solar cells are mounted separately to the textile. The work within this chapter covers both of these potential scenarios. Due to the absence of previous research within this area, the research carried out as described within this section started from a fundamental level, involving photovoltaics that have been mounted separately to the textile rather than integrated into the textile. The research covered two types of photovoltaic cells; rigid cells and flexible cells. These cells have been connected to two types of heater units; a star shaped heater and glass wafer microheaters. The idea for using of a system based on glass wafers was considered for textile applications where sunlight can pass through the system, and also textile applications, which are not back-illuminated, for example a wall-hanging. This chapter presents a detailed analysis into the efficiency of individual batches of

microheaters, which were developed as a result of a collaboration with the Engineering and Physical Sciences Department at Heriot Watt University.

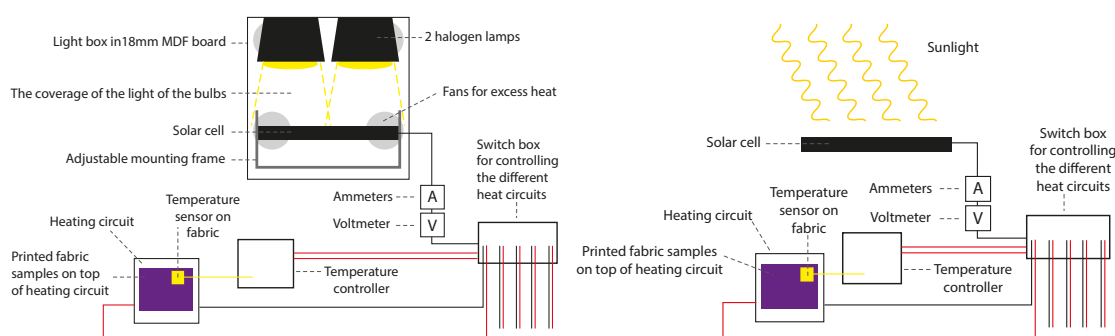
Evidence of the successful proof of concept was provided based on the result that colour change was observed in textile samples printed with thermochromic leuco dyes. In this case, the research was fundamental in nature, focused mainly on the proof on concept rather than on the expression of the design. Monochromatic thermochromic dye samples were observed to change colour using the microheater circuits powered by the solar cells. This produced imageries of small circular patches of colour-changing textile. These small circles would, at times, morph into larger formations. The shape of the colour-changed area of the textile was determined by the form of the microheater units and distance between them, in combination with the amount of sunlight incident onto the photovoltaic.

Another finding from the research described in this chapter, presented in section 6.2, addresses research question Q3 (b). This finding, based on a comparison between the three activation applications, indirect as well as direct solar activation and ‘traditional’ heat circuitry, involves additional contributions to the meaning and use of the ‘design variables’ (‘amount of thermal energy’, ‘heating ability’, ‘time interval/temporal pattern’ and ‘distribution of heat’), which were defined in chapter 4, sections 4.4.1-4.4.7 and 4.5.1-4.5.4. This section also adds to the descriptors for ‘reversible dynamic patterns’ when using the sun as an indirect heater, compared to applications using two alternative activation, mechanisms, direct solar activation and ‘traditional’ heat circuitry. The findings are conclusions drawn from the comparative analysis, based on both the practical experience as described in sections 4.3 and 6.1 as well as theoretical considerations. Section 6.2 aims to provide designers with an understanding of how using traditional heating circuits together with uncontrollable sunlight affects the intended design result when using indirect solar activation, via photovoltaics, to activate thermochromic dyes.

Finally, in section 6.3, a discussion is presented from the perspective of the method of future scenarios, addressing research question Q4, section 1.3. The scenarios demonstrate the author’s vision of the possible use of photovoltaic cells integrated into textile applications. The future scenarios are also projected on the basis of both the practical and the theoretical knowledge gained from this research. The future scenarios provide examples, from a design perspective, to illustrate potential future applications in which integrated photovoltaic cells could be used as activators for textiles treated with

thermochromic dyes, to further strengthen and facilitate the exploration and use of thermochromic dyes within textile design applications. Further, the scenarios illustrate examples of how the dynamic effects of thermochromics, as well as of the light and shadow imageries (which were explored as described in chapter 5), can be utilized within a space. Two conceptual solutions are discussed, one indoors (section 6.3.1.) and one outdoors (section 6.3.2). The scenarios discuss two possibilities for integrating photovoltaics in textiles; (a) stitching, or similar means, flexible cells and (b) printing photovoltaics on to the textile surface. The future scenarios are supported by a discussion, section 6.3.3, based on the findings throughout this thesis as well as other those documented by other researchers within the areas of photovoltaics and textiles. The section elaborates on both what is currently feasible as well as on novel possibilities in the future.

The experimental work of part III, on which the proof of concept of the use of solar energy impacting on photovoltaics as an indirect activator of thermochromics as well as the analysis in sections 6.1.5, 6.2 and 6.3 are based, is methodologically more quantitative and scientific, compared to the approaches described in chapters 4 and 5. However, the investigations reported within this chapter also contain a design approach with qualitative visual observations. These investigations were based on the outdoor set-up J (see Graphic 6.2) using actual sunlight (section 6.1.5), as well as the indoors set-up I (see Graphic 6.1) in which sunlight is simulated using a light box fitted with two 240V halogen lamps (section 6.1.4), specially constructed for the purpose of the investigation.



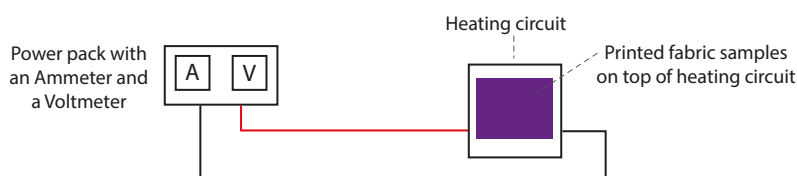
Graphic 6.1-6.2 Set-up I, powering the solar cell with lamps (left) and set-up J, powering the solar cell with natural sunlight (right).

Set-up I was developed to allow the first stage of a laboratory investigation into the potential of using photovoltaics as the power supply without being dependent on the weather conditions. The investigations, using both set-ups, were based on the illuminance values, using the previously defined framework of sunny and cloudy sky

conditions in order to compare the methods of direct indirect solar energy. The illuminance (measured in lux) of sunny sky conditions were in the range 90,000-110,000lux and cloudy sky conditions were in the range 20,000-35,000lux, based both on reference to the literature and on measurements carried out as described in section 3.7.1. Observations of colour change were made both during sunny sky conditions and conditions that were intermediate between the defined ranges of sunny and cloudy sky conditions. The investigations were conducted using a collection of printed samples of dyes with more than one activation temperature (AT) to provide an initial visual understanding of how differences in activation temperature might add to the potential use of the photovoltaics as the energy source.

The quantitative methods were chosen on the basis that they would provide sets of data, which allowed analysis of the impact on the colour change on the textiles printed with thermochromic dyes in relation to the heater used and the power created by the photovoltaic. The diameter (and therefore area) of the circular colour changed areas were measured in order to compare the power outputs produced by the photovoltaics. The measurements were conducted both initially when the circuit was immediately switched on as well as later when an apparent difference within the colour change had been observed. The time, in minutes, from switching on the circuit, to when the colour-changed areas were measured, was recorded to include information on how quickly the samples printed with the dyes with different activation temperatures became activated, as well as to demonstrate an increase in the spread of colour-change.

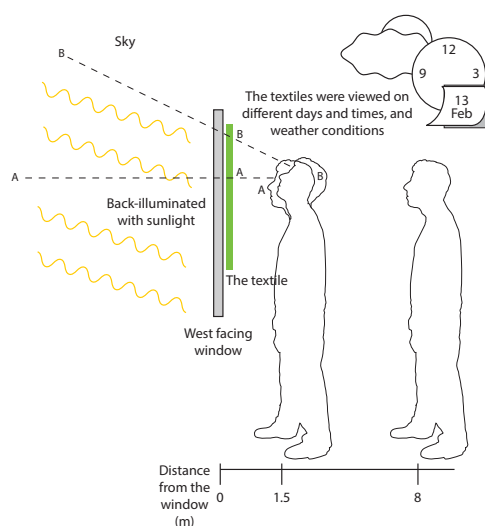
The scientific method quantifying the power output of the glass wafer based microheaters (presented in section 6.1.3), powered using a 0-10A 0-3V adjustable DC power pack, was used during the process of evaluating and optimizing the construction of the microheaters. This investigation was carried out by establishing the relationship between the current (I) and the measured size of the activated area in the printed sample, as the voltage (V) was increased gradually (see set-up H, Graphic 6.3).



Graphic 6.3 Set-up H, powering the heat circuits with a power pack.

Further, the method was also used as a means to establish the potential of using the photovoltaic cells as the power source, by comparing the power output with illuminance values (section 6.1.4). Different substrate qualities were used in an investigation with a quantitative approach using set-up I and the glass wafer circuit to estimate whether the thickness of the substrate would lead to an increase in the size of the colour-change area (section 6.1.3).

The different substrate qualities were observed to assess qualitatively the effect on the visual clarity of the colour-changed area in the sample, using set-up I (see Graphic 6.1) and the rigid star-shaped circuit. As a result of these observation was that the satin substrate quality was used in the subsequent investigations (section 6.1.2). Qualitative observations were also conducted as described in section 6.3, using set-up A (see Graphic 6.4). The study aimed to determine whether a photovoltaic that is incorporated (glued onto the surface) with a textile printed with thermochromic dyes would have the potential to influence the activation of the dye, via the spread of the area of the colour change. Indoor observations using set-up A (see Graphic 6.4), previously used as described within chapter 4 and 5, were carried out in a detailed controlled manner. For example, the position of the observer and sample as well as the distance between observer and sample were kept constant in order to ensure a controlled framework for the observations, to minimise the consequences of the subjective nature of the observer's visual perception.



Graphic 6.4 Set-up A visually observing the textile samples.

Experiments were also conducted that demonstrated that photovoltaic cells could facilitate as indirect heaters for thermochromic dyes. It was found that the activation was achieved in a time shorter on the areas of printed textile in contact with

photovoltaic cells on the fabrics non-printed side, compared to areas not in contact with the cells. The observed result was correlated with an investigation using the quantitative, scientific approach, by measuring the temperature curve with a microprocessor controlled handheld thermometer, Graph 6.1.

6.1 The potential of using photovoltaic solar cells to power printed thermochromic dyes

The main result of the research described in this section is the proof of the concept, which demonstrates that photovoltaic cells may successfully be used as an energy source to power electrical heating mechanisms that in turn activate thermochromic textiles. A number of notable designers, including Orth and International Fashion Machines (Seymour 2008, p.75), XS Labs (Berzowska and Bromley 2007, p.2), Worbin (Worbin 2010, p.146) and Berzina (Seymour 2008, p.183) have experimented with the use of thermochromic materials, aiming to exploit the dynamic colour change properties. Most commonly, they have used electrical heating mechanisms to activate the dyes in design applications for fashion and interior textiles. The electrical heaters incorporated in these applications are powered by traditional supplies not directly linked to renewable energy sources. (Seymour 2008) In this thesis, it was therefore considered to be of vital importance to investigate the potential of a system powered by renewable energy as defined in research question Q2, section 1.3.

6.1.1 *Initial tests to activate thermochromic dyes via energy powered with rigid solar cells*

This section demonstrates the initial test using a photovoltaic as an energy source. Prior research by the author (Ledendal, 2009), carried out on printed textiles with integrated embroidered and knitted electrical circuits that were powered by power packs, provided the experience that a relatively high power output was needed to change the colour of thermochromic dyes with the rather inefficient heaters that were used. On the basis of this knowledge and of the experience of collaboration with Dr. Wang, the initial exploratory testing was conducted with rigid solar cells using an external heater based on a 33ohm Meggitt resistor (relatively high resistance, see section 3.11). The system involved indoor set-up I, as illustrated in Graphic 6.1, with the printed fabrics placed directly on top of the resistor. The single resistor was connected to the rigid BP solar cell. The dimmer controlling the brightness level of the illuminators in the light box

was set to maximum, to simulate a sunny sky. This set-up was found to provide surface temperatures on the resistor of above 57°C (see Figure 6.1).

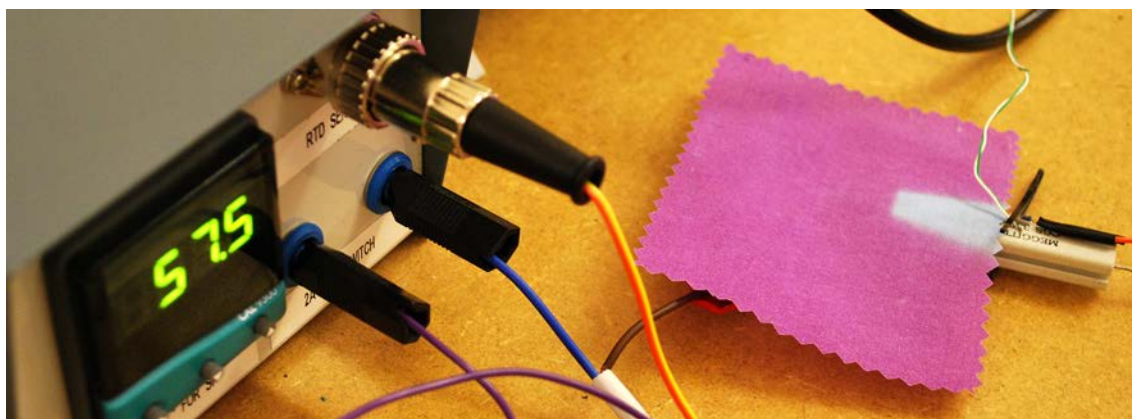


Figure 6.1 The measured temperature of the colour changed area on the printed sample using the Meggitt resistor and the rigid photovoltaic. The activated thermochromic area takes the shape of the resistor.

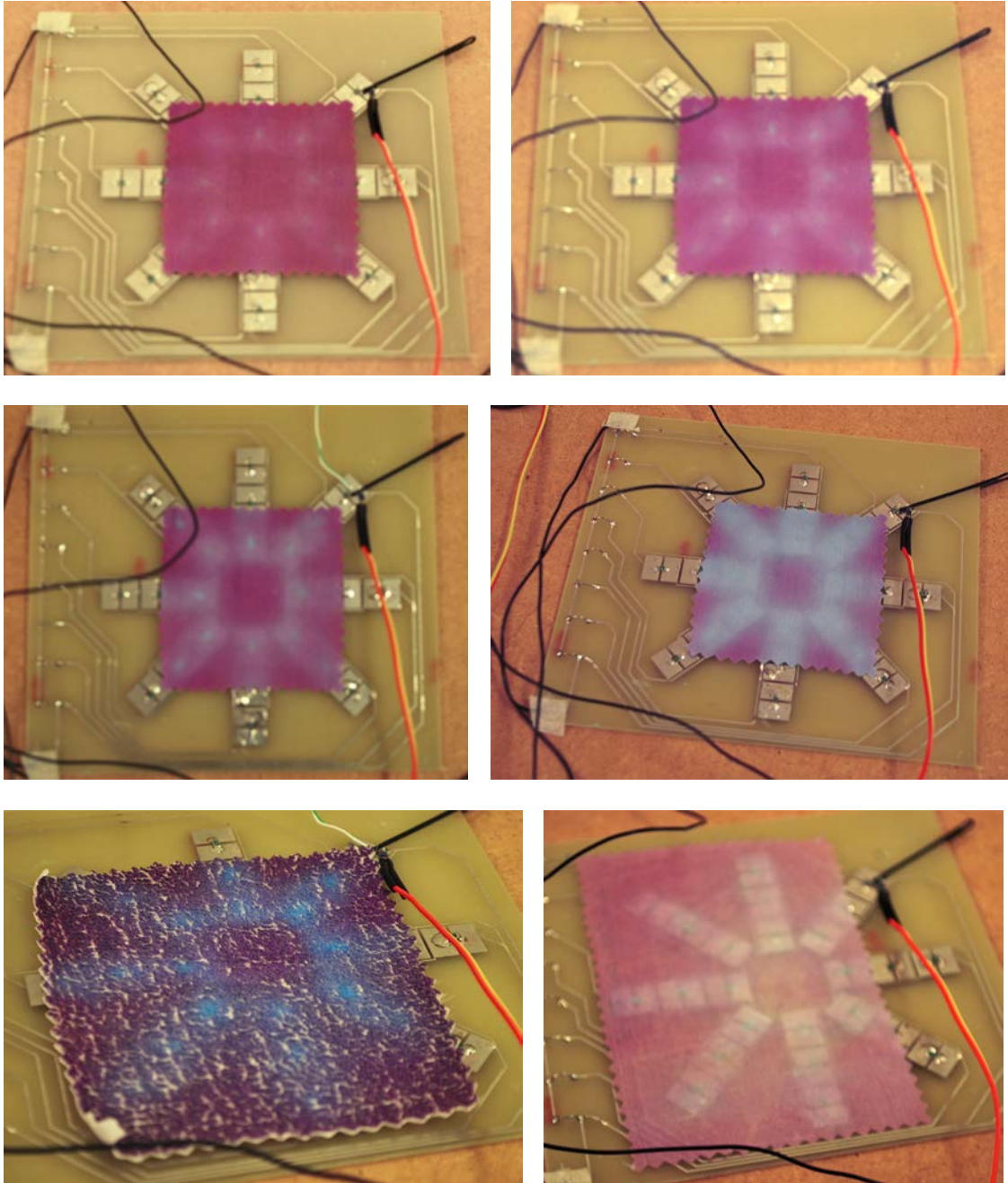
This created colour changes on the thermochromic fabrics that mimicked the shape of the resistor. The fabrics were printed with dyes having activation temperatures up to 48°C. These initial experiments provided a positive demonstration that thermochromics could be activated using the power from solar cells. This knowledge was used in subsequent investigations with more complex electrical heating mechanism.

6.1.2 *Activating thermochromic dyes via a photovoltaic solar cell in combination with a rigid heating circuit using indoor set-up I*

This section presents the next phase of the investigation into the potential of activating thermochromic dyes via solar energy, using a star-shaped, opaque, rigid circuit as a heater. This heating circuit had previously been used successfully in the work of Dr. Sara Robertson. In her work, the heating circuit was powered by a 0-10A and 0-3V adjustable DC power pack in order to activate the thermochromic dyes. The circuit was fitted with eight arms, each with three 150ohm (0.65mm x 1.65mm) resistors. Each resistor was connected to two 0.5x1cm copper metal plates. The star-shaped heating circuit took 5 minutes to reach 47°C, when the input voltage input was 6-7V. (Robertson, 2011, pp.62-63)

In this present study, the star-shaped circuit was connected to the BP rigid solar cell, using indoor set-up I, Graphic 6.1. The lamps, in the light-box, were mounted at an approximate distance of 15cm from the solar panel. The dimmer was set at maximum, around 72,000-97,000lux, to simulate sunny sky (90,000-110,000lux) outside. Cloudy sky conditions within set-up I was set at a lux value in the range 20,000-35,000lux. The

sky conditions (sunny and cloudy sky) for set-up J (see Graphic 6.2) were assessed as defined in section 3.7.1, by judgement of the percentage clouds and actual measured lux values. As before, the printed textiles (silk-chiffon, silk-viscose satin and velvet samples) were placed on top of the circuit, one at a time. The thermochromic dyes used in these experiments had an activation temperature of 27°C.



Figures 6.2-6.5 (top four) The activated imagery on the printed silk-viscose satin sample using the star-shaped circuit and the rigid photovoltaic. Figure 6.6 (bottom left) Example of activation using the silk-viscose velvet substrate, using the star-shaped circuit and the rigid photovoltaic. Figure 6.7 (bottom right) The colour change on the printed silk-chiffon sample was not visible since the star-shaped circuit was visible through material.

A colour-changing star-shaped imagery was observed within the silk-viscose samples (the satin and the velvet) after around 10 minutes (see Figures 6.2-6.6). The temperature controller registered a temperature of 31.5°C when the imagery fully changed colour. In the case of the silk-chiffon, the fabric was too thin and transparent, which meant that the colour change was not visible and only the background circuit was observed (see Figure 6.7). The use of silk chiffon was therefore discontinued for further tests. The positive aspect of the experiments using the star-shaped circuit was that it proved the concept that solar energy could be harvested to power a heating mechanism that activates textiles printed with thermochromic dyes. However, in these studies, the opaque base of the heating circuit blocked out all sunlight. This type of heater would be suitable for applications where the textile is not transparent so that sunlight does not pass through the textile. This feature fits well with certain applications, such as for example if the textiles printed with thermochromic dyes are located indoors while the photovoltaics are mounted on a facade or roof of a building, but not with the particular sun-screening applications that are the focus within this thesis. The construction of the star-shaped circuit was, additionally, rather rough because of the soldered components, so that the fabric did not lie flat enough against the surface of the circuit, as the distance between the base and the top of the heaters was too large.

6.1.3 *Microheaters electroplated on a glass base*

The collaborative programme of research leading to the development of the glass wafer based microheaters is presented in this section. The process of evaluating and optimizing the construction of the microheaters was conducted by measuring as well as visually observing the colour changed area on the printed textile samples, in relation to the power output from the microheaters. The investigation was conducted using set-up H with a power pack as the power source (see Graphic 6.3).

As the next phase of the research circuits were custom made, constructed with the aim to produce a more unobtrusive heater with a high heat output based on a relatively low power input, compared to those investigated previously. In order to make it more unobtrusive, a transparent glass base was used and there was an aim to create a more even and interlaced surface between the base and the circuits. Furthermore, the aim was to create a more subtle circuit construction that would be anticipated to provide less interference with the aesthetic expression within the printed sun-screening textiles, using small, but efficient, heaters. Therefore, a solution to this design problem in the

form of a 'state of the art' nickel and titanium based circuit was devised in collaboration with Dr. Changhai Wang, Prof. John Wilson and PhD student Soni Chandrasekar of the Electrical Engineering Departments of Heriot-Watt University involving construction by electroplating circuits onto glass wafers. The circuits were constructed to provide highly efficient microheaters, which produce a high thermal output in relation to their size. The requirement of a thin and smooth surface was obtained through electroplating as the circuits were applied onto the base. Compared to, for example, the heaters soldered in the star-shaped circuit which was used in the tests described in section 6.1.2, electroplating created a much more unobtrusive circuit. For example, the circuit components cannot be felt when a finger is run over the circuit.

The reasons for using glass as the base of the circuit were the following:

- (a) allows larger amounts of sunlight to pass through both the textile and the heating circuit base;
- (b) has the potential to retain the partial visibility through the more translucent textiles (for example, the structures described in chapter 6 through laser technology and devoré print);
- (c) likely to have low impact on the colour outcome of the printed thermochromic dyes;
- (d) fabrics that had been mounted on glass (windows) for observations described in chapter 4 using the indoor set-up A (see Graphic 6.4), provided experience of how the material affects the colour change due to temperature increases in the glass.

The microheaters were connected in parallel and grouped in five individual circuits, as illustrated in Figure 6.8. The five circuits were different, fitted with either 2, 3, 5, 6 or 7 microheaters, a total of 23 microheaters on each glass wafer. Each individual microheater had a resistance of 3 ohms. The microheaters were spaced between 7 and 12mm apart. Wires were soldered on to the positive and negative terminals (illustrated with red and black circles respectively in Figure 6.8) using conductive silver paint. The active heater closest to the positive terminal, in the individual circuits, was labelled as 'heater 1' and the activated area on the fabric on top of that heater was labelled 'area 1' (see 'heater 1', Figure 6.8). The remaining active heaters and corresponding activated areas were numerically labelled based on how far they were from the positive (see 'heater 5', Figure 6.8).

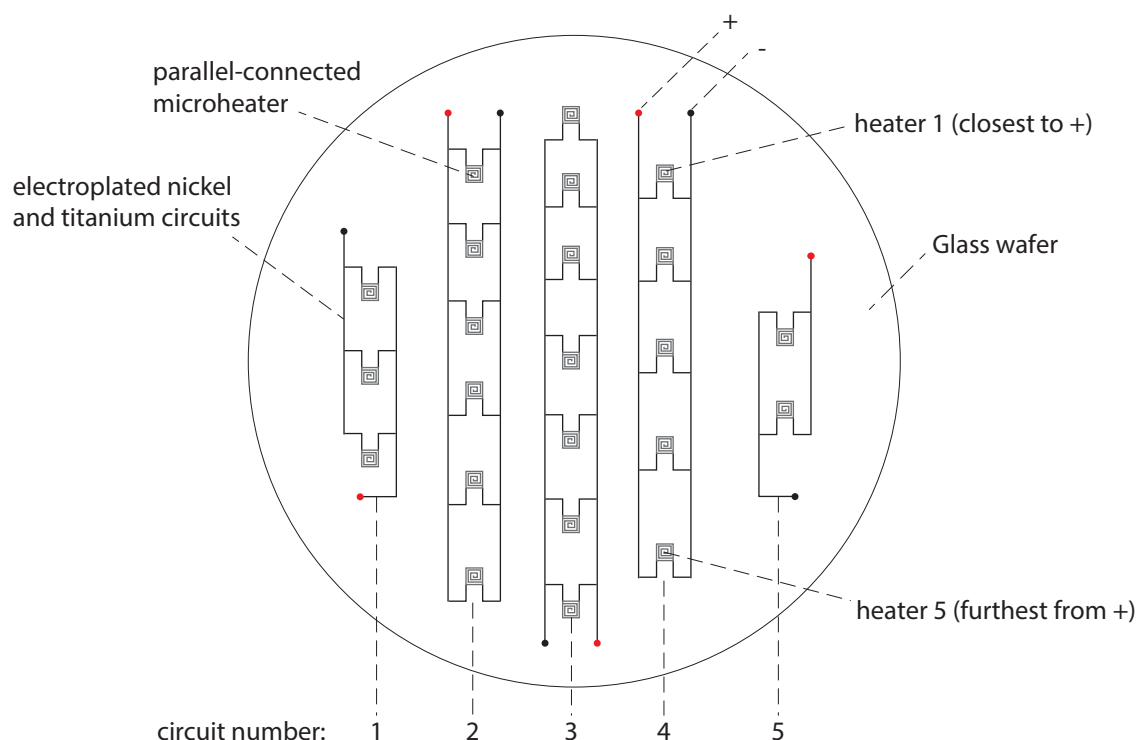


Figure 6.8 Illustration of the layout of the circuits on the glass wafer

The development of the electroplated circuits on glass wafers was carried out as three different batches labelled as batches 1-3. Each batch of the electroplated circuits consisted of 2-3 experimental variations in terms of the detailed nature of the construction and the materials, labelled as wafers A, B and C of batch X. Initially, set-up H, Graphic 6.3, as described in section 3.11, with a 0-10A and 0-3V adjustable DC power pack as the power source was used to establish the relationship between the current (I) and the measured size of the area activated in the printed sample, as the voltage (V) gradually was increased (see Table 6.1 for a selection of results for batch 1). The power output (P) was calculated using the equation $P = IV$. Each subsequent batch was based on the version (wafer A, B or C) within the previous batch that had provided the lowest required power in relation to largest size of activated printed area. Because of the delicate and experimental nature of the construction, it was found that not all heaters were active within each individual circuit. However, as expertise developed in the collaboration, the number of active heaters increased from only 1-2 per individual circuit in the first batch to the majority of heaters in the final batch.

Measurements on the first batch of glass wafers (batch 1, wafers A and B) were carried out on silk-viscose satin printed with thermochromic dyes with an activation

temperature of 27°C, see Table 6.1, in order to compare the power and the activated area on the satin in relation to number of active heaters.

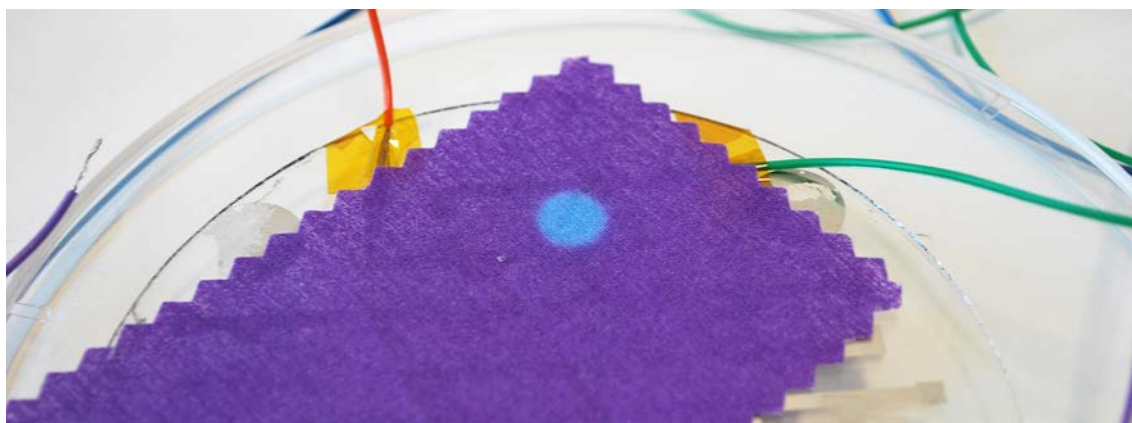
Table 6.1 Current (I), voltage (V) and power (P) when running circuits on glass wafer, batch 1.

Set-up (x/y)*	I (A)	V (V)	P (W)	Comment
1 circuit (circuit 5), 1/2 heaters	0.04	1.0	0.04	A slight blue tint was observed.
	0.07	1.5	0.11	A circle appeared in area 1 with $\varnothing = 5\text{-}6\text{mm}$. A sharp edge on the outline.
	0.09	2.0	0.18	The circle expanded with $\varnothing = 8\text{-}9\text{mm}$. Still a sharp edge.
	0.10	2.5	0.25	The circle expanded with $\varnothing = 1.3\text{-}1.5\text{cm}$. Still a sharp edge.
1 circuit (circuit 2), 2/5 heaters	0.08	2.0	0.16	Blue circles appeared in areas 1 and 2 with $\varnothing = 6\text{mm}$. Sharp edges on the outlines.
	0.10	2.5	0.25	The circles expanded with $\varnothing = 8\text{-}9\text{mm}$. The area in-between the two circles started to colour change.
	0.11	3.0	0.33	The two activated areas morphed together. The surface temperature of the textile measured 34.5°C over the heaters and 30.6°C centred between the heaters.
1 circuit (circuit 3), 2/7 heaters	0.09	2.0	0.18	There were obvious size differences between the two activated areas; area 1 measured $\varnothing = 9\text{mm}$ and area 2 $\varnothing = 5\text{-}6\text{mm}$. The two areas morphed together.
	0.11	2.5	0.28	The activated area expanded.
	0.12	3.0	0.36	The activated area continued to expand.
2 circuits (number 2 and 3), 4/12 heaters	0.14	1.5	0.21	No activation within the sample.
	0.17/ 0.18	2.0	0.36	Four activated circles appeared. Heater 1 in circuit 3 activated the fabric quicker compared to the circuits remaining heaters. The activated area 1/circuit 3 and area 2/circuit 3 morphed together. Area 1+2/circuit 3 morphed with area 1/circuit 2. All four activated areas slowly morphed together.
	0.20/ 0.21	2.5	0.5/ 0.53	The activated organic shaped area expanded.
2 glass wafers: Wafer A: 1 circuits (number 5), 1/2 heaters Wafer B: 2 circuits (number 2 and 3), 4/12 heaters	0.22	1.5	0.33	Wafer A: Area 1/circuit 5 activated a circle with $\varnothing = 5\text{mm}$. Wafer B: A slight colour change was viewed in the areas.
	0.27	2.0	0.54	All five circles provided a clear colour change. Areas 1/circuit 5 and area 1/circuit 3 each measuring $\varnothing = 7\text{mm}$ and area 2/circuit 3 and area 1-2/circuit 2 each measuring $\varnothing = 5\text{mm}$. Areas 1-2/circuit 5, in wafer B slowly morphed.
	0.31/ 0.32	2.5	0.78/ 0.8	Wafer A: Area 1/circuit 5 activated circle with $\varnothing = 1.2\text{-}1.3\text{cm}$. Wafer B: Areas 1-2/circuit 5 morphed with area 2/circuit 3. Slowly this morphed area also morphed with area 1/circuit 3, creating a large organic shape.

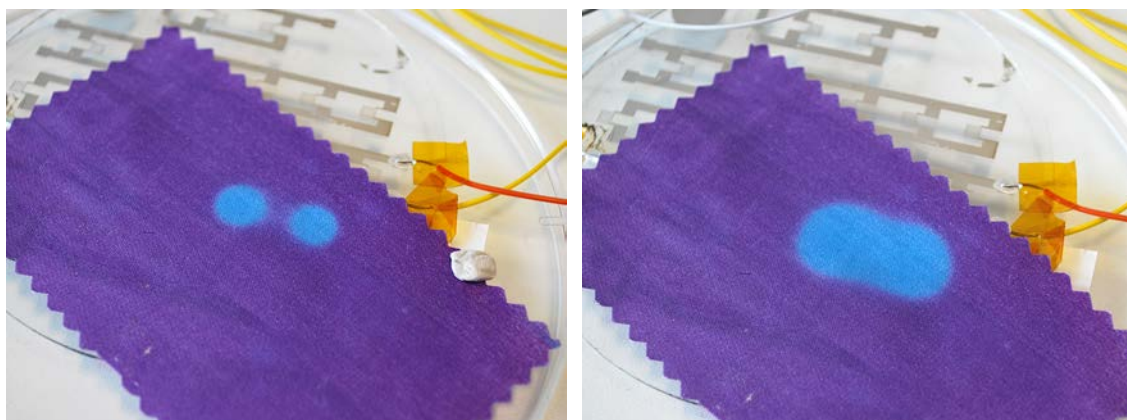
* The number of active heaters (x) out of the total number (y) within the circuit.

One active microheater from batch 1 required around 0.18W (0.09A and 2V) to activate the printed dark purple chromic dye, so that a blue circle due to the presence of a

permanent blue pigment with diameter (\varnothing) 9-10mm was created (see Figure 6.9 and Table 6.1). In this instance, the temperature on the surface of the fabric centred over the microheater was 34-35°C. Two active microheaters, spaced 12mm apart, connected in parallel within one circuit, required 0.25W (0.10A and 2.5V) to activate a similar circle with \varnothing = 9-10mm (see Table 6.1). A power of 0.33W (0.11A and 3V) was required to extend the two activated circular areas so that they morphed into one oval (see Figures 6.10-6.11).



Figures 6.9 Activated area on fabric, using one active microheater from batch 1.



Figures 6.10-6.11 Activated fabric, using two active microheaters from batch 1. Figure 6.11 (right) The area between the two colour changed circles in Figure 6.10 has morphed into one large oval area.

Four individual activated circles, created from four active microheaters (two microheaters in each of two circuits), morphed by combination into an organic shape before the individual circles had reached \varnothing = 9-10mm. The activated circles started to morph into one organic area by 0.36W (0.17-0.18A and 2V) (see Figures 6.12-6.13 and Table 6.1).

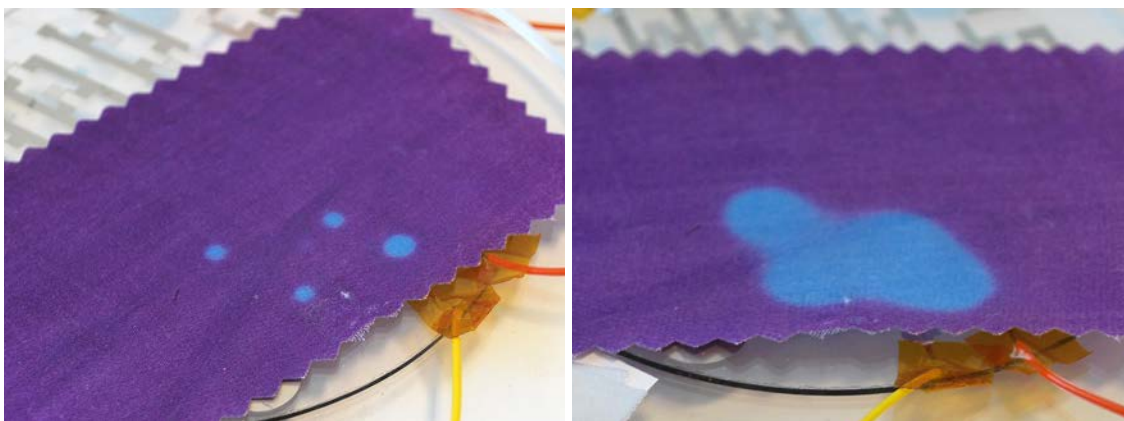


Figure 6.12-6.13 Activated areas on fabric, using four active microheaters, from two different circuits, from batch 1. Figure 6.13 (right) The area between the four colour changed circles in Figure 6.12 has morphed into one large organically shaped area.

Similar results were observed when three circuits with a total of five microheaters (two circuits, wafer B, each with two active heaters as well as one circuit, wafer A, with one active heater) were tested (see Table 6.1). The four circles that were created on the fabric, covering wafer B, were observed to morph when the power measured 0.8W (0.31-0.32A and 2.5V). The individual circle on the fabric covering wafer A measured $\varnothing = 1.2\text{-}1.3\text{cm}$ (see Figure 6.14).

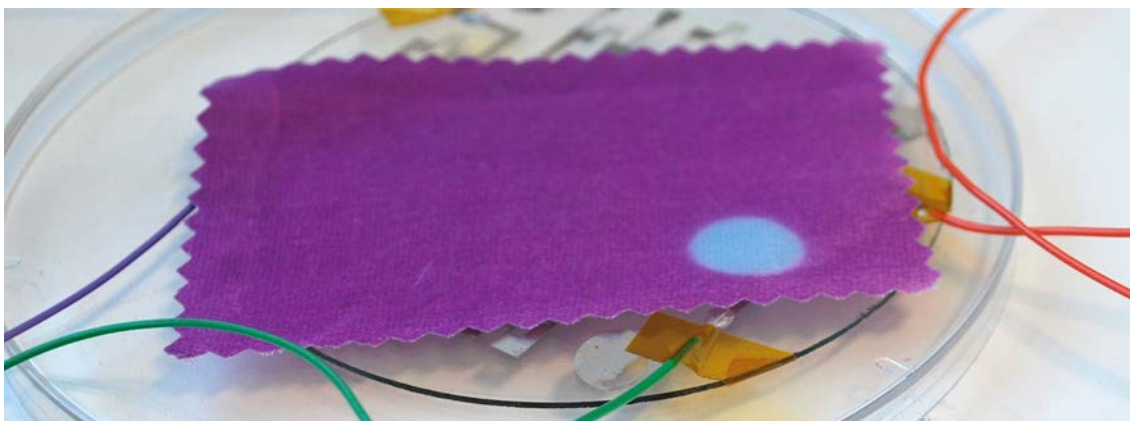


Figure 6.14 The activated circular-shaped area on the individual fabric covering wafer A, when three circuits with a total of five microheaters was used. The activation on the other fabric, covering wafer B, very much acted as previous tests in Figures 6.12-6.13.

The majority of the initially activated areas created a circular shape with a sharp edge (see Figures 6.9-6.14). The exceptions were the samples that were printed with a colour that was based on more than one thermochromic dye. These samples provided a more gradual colour change between the inactivated light or dark purple and the activated light or dark blue colour states (see Figure 6.15). These purple colours were

mixed with red as well as black leuco dyes and a permanent blue pigment, as defined in the dye recipes in appendix A.

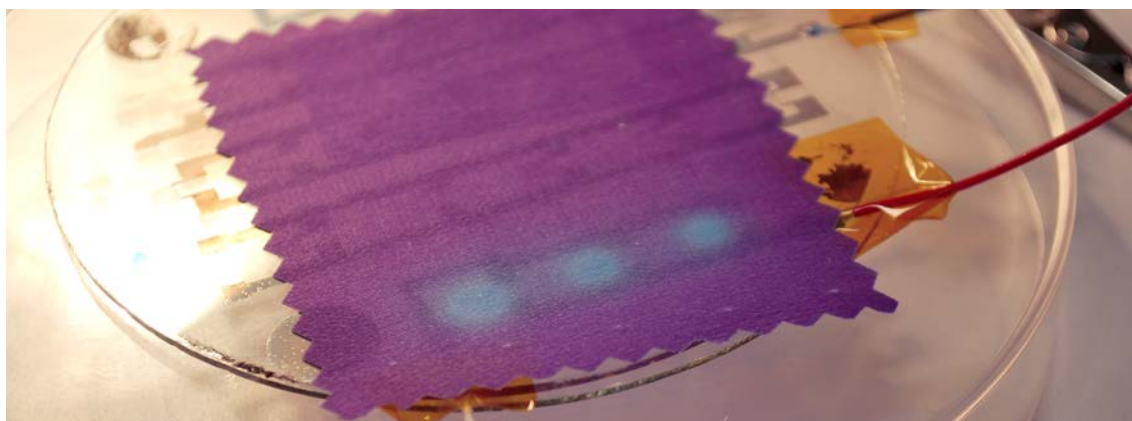


Figure 6.15 Samples with a more gradual colour change between the inactivated purple and the activated blue colour states.

Further tests were carried out with silk-viscose satin printed with thermochromic dyes with activation temperatures of 31°C and 47°C. The measurements were carried out with wafer A, batch 1, using circuit 1 with one active heater. The tests, however, demonstrated that the differences in the diameters of the activated circular areas were rather small when an identical voltage was applied. A voltage of 2V provided an activated circle with $\varnothing = 9\text{-}10\text{mm}$ for an activation temperature at 27°C, $\varnothing = 9\text{mm}$ at 31°C and $\varnothing = 5\text{-}6\text{mm}$ at 47°C (see Table 6.2).

Table 6.2 Current (I), voltage (V) and power (P) when running circuits on glass wafer, batch 1.

Activation temp./fabric	I (A)	V (V)	P (W)	Comment
31° silk-viscose satin	0.04	1.0	0.4	A circle appeared in area 1. Fuzzy edge in the outline.
	0.07	1.5	0.11	The circle expanded with $\varnothing = 5\text{-}6\text{mm}$. Edge still fuzzy.
	0.08	2.0	0.16	The circle expanded with $\varnothing = 9\text{mm}$. The surface temperature of the textile measured 34.3°C.
	0.10	2.5	0.25	The circle expanded with $\varnothing = 1.4\text{cm}$.
47°C silk-viscose satin	0.08	2.0	0.16	A circle appeared with $\varnothing = 5\text{-}6\text{mm}$. A sharp edge on the outline.
	0.10	2.5	0.25	The circle expanded with $\varnothing = 10\text{mm}$.
27° silk-viscose velvet	0.05	1.0	0.05	A slight blue tint was observed.
	0.07	1.5	0.11	The circle expanded with $\varnothing = 5\text{-}6\text{mm}$. A sharp edge on the outline.
	0.09	2.0	0.18	The circle expanded with $\varnothing = 8\text{mm}$.
	0.10	2.5	0.25	The circle expanded with $\varnothing = 1.2\text{-}1.3\text{cm}$.
27°C silk	0.05	1.0	0.05	No colour change was observed. The imagery was transparent and

chiffon				the circuit was visible through the fabric.
	0.05	1.0	0.05	A very slight blue colour, hardly noticeable, was observed.
	0.07	1.5	0.11	The circle expanded with $\varnothing = 6\text{mm}$. Fuzzy edge in the outline.
	0.09	2.0	0.18	The circle expanded with $\varnothing = 10\text{mm}$. The blue colour was difficult to observe in the readings with silk chiffon, due to the thin fabric.
27°C polyester- viscose	0.04	1.0	0.04	No colour change was observed.
	0.07	1.5	0.11	The circle expanded with $\varnothing = 4\text{-}5\text{mm}$. A sharp edge on the outline.
	0.08	2.0	0.16	The circle expanded with $\varnothing = 9\text{mm}$.

Additional tests were carried out on silk-chiffon, polyester-viscose and silk-viscose velvet (printed with activation temperature 27°C dyes) to investigate whether the diameter of the activated circle would alter significantly due to substrate thickness (see Table 6.2 and Figures 6.16-6.17). The thicker material, as expected, demonstrated a need for a slightly higher voltage compared to the thinner satin fabric, although the differences proved to be more marginal than might have been envisaged based on the material's thickness. The thickest material, velvet, produced a circle of $\varnothing = 8\text{mm}$, while the thinner materials created slightly larger circles; $\varnothing = 10\text{mm}$ for chiffon, $\varnothing = 9\text{-}10\text{mm}$ for silk-viscose satin and $\varnothing = 9\text{mm}$ for the polyester-viscose, all using 2V (see Table 6.1 and 6.2).

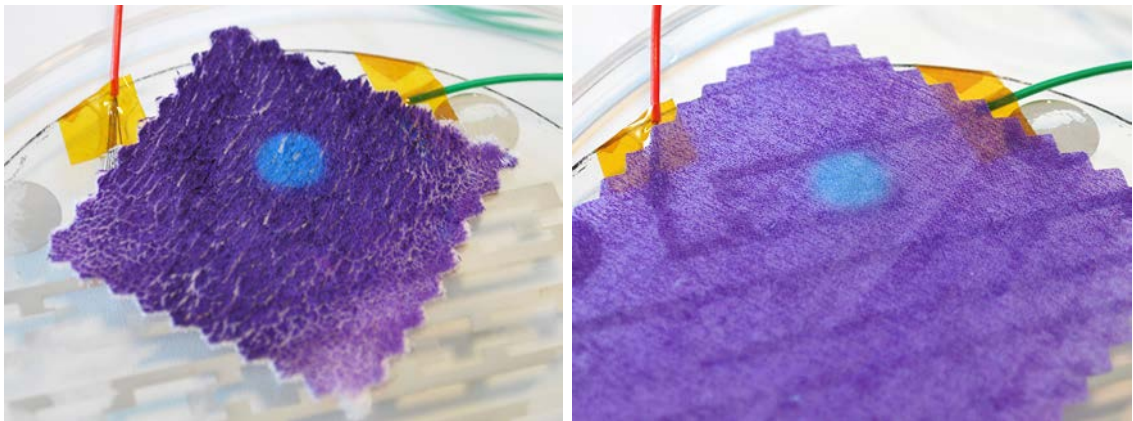


Figure 6.16 (left) Activated area on a silk-viscose velvet sample, using one active microheater from batch 1. Figure 6.17 (right) Activated area on a polyester-viscose sample (same heater as in Figure 6.16).

The second and third batch of electroplated glass wafers resulted in more optimised heating circuits, with a higher percentage of active heaters and more effective power output. The samples, as illustrated in Figure 6.18-6.19, successfully morphed the printed areas over the active heaters on the fabric with circuits of up to 9 active heaters.

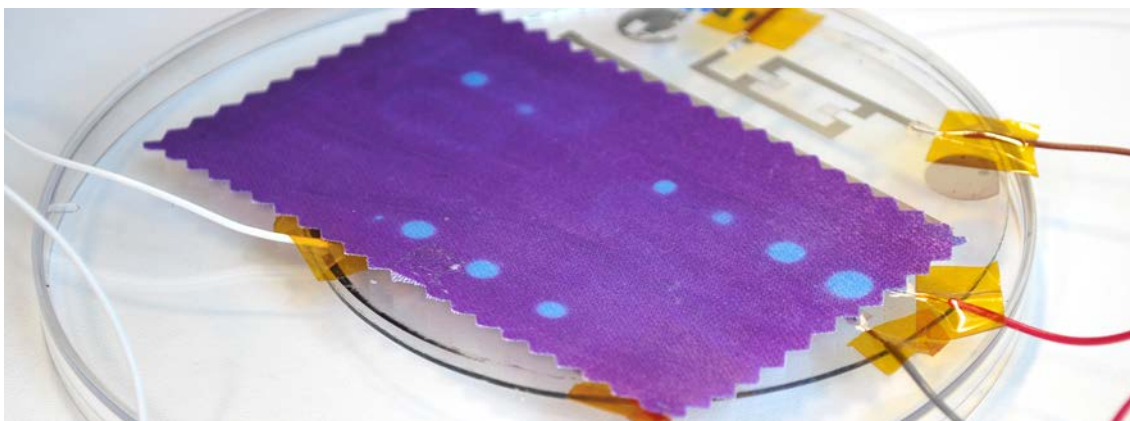


Figure 6.18 Activated areas on a silk-viscose satin fabric, using nine active microheaters, from two different circuits, batch 3.

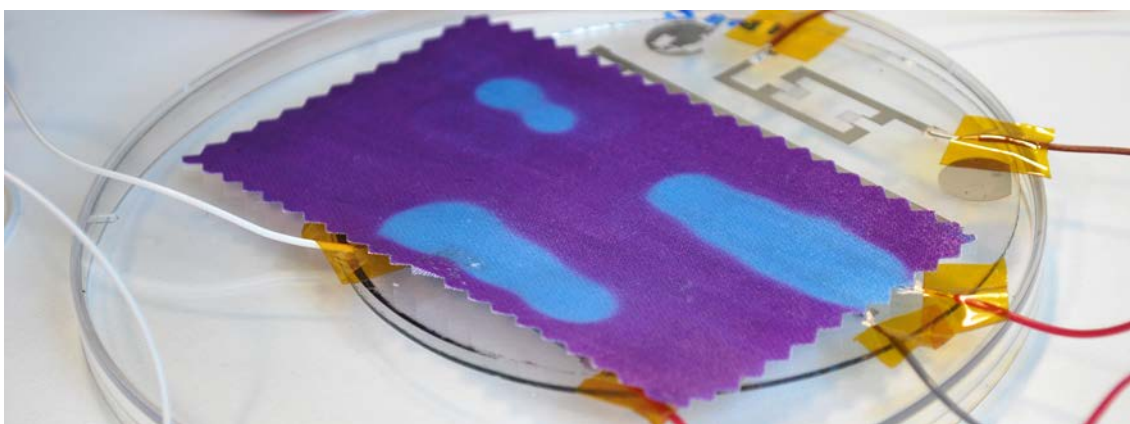


Figure 6.19 The areas between the individual groups of colour changed circles in Figure 6.18 has morphed into three individual large areas.

A comparison of the power of the circuits and wafers (A and B) of the third and final batch at a constant voltage of 2V were carried out on a silk-viscose satin fabric that was printed with thermochromic dyes with an activation temperature at 27°C. Results from this comparison are presented in Table 6.3. The construction of wafer A provided somewhat more effective measurements, with slightly lower power output compared to wafer B (see Table 6.3). Therefore, version A was used for the initial tests with set-up I (see Graphic 6.1) using the light box to power a rigid photovoltaic cell as the power supply.

Table 6.3 Current (I), voltage (V) and power (P) when running circuits on glass wafer, batch 3.

Set-up (x/y)*	I (A)	V (V)	P (W)
Wafer A, circuit 5, 1/2 heaters	0.23-0.22	2.0	0.46-0.44
Wafer A, circuit 1, 3/3 heaters	0.66-0.64	2.0	1.33-1.28
Wafer A, circuit 3, 6/7 heaters	0.97-0.92	2.0	1.94-1.84
Wafer A, circuit 1 and 3, 9/10 heaters	1.52-1.51	2.0	3.04-3.02
Wafer B, circuit 5, 1/2 heaters	0.26	2.0	0.52

Wafer B, circuit 2, 4/5 heaters	0.66	2.0	1.32
Wafer B, circuit 3, 6/7 heaters	0.98	2.0	1.96

* The number of active heaters (x) out of the total number (y) within the circuit.

6.1.4 *The potential to activate thermochromic dyes via photovoltaic cells connected to microheater circuits*

This section presents the investigations carried out using indoor set-up I (see Graphic 6.1), where sunlight is simulated using a purpose-built light box fitted with two 500W halogen lamps. This set-up was devised to facilitate a first stage laboratory investigation into the potential of using photovoltaics as the power supply where the intensity of incident light could be kept constant. The potential for success in using the photovoltaic was analysed using both quantitative and qualitative (visual observations) assessment of the colour changed area on the printed textile samples. The compiled data were evaluated in relation to the power output from the microheaters as well as the measured illuminance values from the halogen lamps.

In this phase of the research, attention moved from the use of mains electricity to solar power. The most apparent difference in output between using the power pack and a photovoltaic cell is the voltage. The voltage from the power pack can be varied and can take any value in its range. The voltage output from the photovoltaic cell, however, is dependent on the level of illumination on the solar cells at a particular time and therefore cannot be controlled in the same way. The measured voltage with photovoltaics in the experiments in this thesis was lowest when the system was initially switched on. However, the voltage subsequently increased and then steadied out some time after the circuit was switched on. Also, the voltage is dependent on electrical load: the higher the load (the more resistance within the circuit) the larger the voltage drop. (Harrop, 2009a and 2009b)

Set-up I, with two lamps placed in a light box as illustrated in Graphic 6.1, was constructed to simulate the light from the sun outdoors during the two defined sky conditions (sunny and cloudy sky). The illuminance (measured in lux) of the sky conditions, sunny sky with values in the range 90,000-110,000lux and cloudy sky in the range 20,000-35,000lux, were defined through both literature references and measurements carried out as stated in section 3.7.1. The measurements using set-up I varied depending on where, over the photovoltaic, the luxmeter was placed. Within this section, the illuminances that are given in the tables were measured at the centre of the photovoltaic cell surface. Also, the illuminance

of the light incident on the photovoltaic varied, as illustrated in Table 6.4, depending on the distance between the photovoltaic and the lamps in the light box.

Table 6.4 Lux-values for two settings PV-distant and PV-close *

Amount of light	PV-distant (lux x 10 ⁻⁴)	PV- close (lux x 10 ⁻⁴)
Dimmer turned up 100%	7.5-8.5	8.7-9.7
Dimmer turned up 92%	7.5-8.15	8.4-9.5
Dimmer turned up 83%	5.5-6.5	7.5-8.5
Dimmer turned up 75%	3.8-4.5	5.0-5.6
Dimmer turned up 67%	2.0-2.5	2.9-3.1
Dimmer turned up 58%	1.4-1.45	1.5-1.6

* The given values of the settings (PV-distant and PV-close) are based on the measured lux values from the illuminance of the area centred under the bulbs on the surface of the photovoltaic.

The experiments were carried out using two distances between the photovoltaic cells and the bulbs: 18-20cm between the cell and the bulbs (referred to as *PV-close*) and 22-25cm between the two (*PV-distant*) (see Table 6.4). The results of the measurements with the PV-distant setting provided a lower illuminance that was more evenly distributed over the surface of the photovoltaic, based on observation of the measurements. The illuminance of the area by the edges of the cell was only slightly lower than in the centre of the cells with PV-distant. The PV-close setting, which gave higher measured lux values, displayed a larger difference between the illuminance measured in the centre of the photovoltaic (the defined values) and at the edges. The central brightest area with PV-close covered a smaller proportion of the total area of the surface of the cell compared to PV-distant. The dimmer of the light box was initially set at the maximum setting (around 72,000-97,000lux depending on the placement of the photovoltaic) to maximize the effect of the rigid photovoltaic in order to simulate sunny sky (90,000-110,000lux). Cloudy sky was simulated by dimming the lights in the light box to between 58-65% of full illumination strength, so that the illuminance of a cloudy sky (20,000-35,000lux) was obtained (see Table 6.4).

The experiments with the rigid photovoltaic, supplied by Marlec Renewable Power, were carried out using the glass wafer circuits (batch 3) and a sample printed with thermochromic dyes with activation temperatures of 27°C, 31°C and 47°C (see Table 6.5). The initial experiments were carried out in the evening to minimize any influence of extraneous light from the sun affecting the results.

Table 6.5 Current (I), voltage (V) and power (P) when running circuits, batch 3 during sunny sky *

Set-up (x/y)**	I (A)		V (V)		P (W)	
	1 st reading	2 nd reading	1 st reading	2 nd reading	1 st reading	2 nd reading
Circuit 5, 1/2 heaters	0.26	0.4	2.0	2.75	0.52	1.1
Circuit 1, 3/3 heaters	0.36	0.36	0.99	1.10	0.36	0.40
Circuit 4, 4/6 heaters	0.37	0.37	0.65	0.67	0.24	0.25
Circuit 3, 6/7 heaters	0.36	0.36	0.53	0.54	0.19	0.19

* The 1st reading was carried out as the system was turned on and the 2nd reading was taken when an apparent difference within the colour change was observed, varying from being inactive to providing an initial activation or an expansion or morph of the initial circular activation.

** The number of active heaters (x) out of the total number (y) within the circuit.

The rigid photovoltaic in set-up I during simulated sunny sky successfully provided enough electrical power to activate the printed surface of the silk-viscose satin samples (activation temperature 27°C) to morph all or parts of the heated areas when circuits with up to 4 heaters were used (see Table 6.5). Wafer A, circuit 1 (3 out of 3 active heaters), and setting PV-close, provided power of approximately 0.36W (0.36A and 0.99V) just as the system was turned on, which almost immediately created 3 small circles with $\varnothing = 5\text{mm}$ on the printed fabric. The power quickly increased to approximately 0.4W (0.36A and 1.1V) causing the circles to expand to $\varnothing = 7\text{-}8\text{mm}$, and 12 minutes after the circuit was turned on they morphed into an oval (see Figure 6.20).

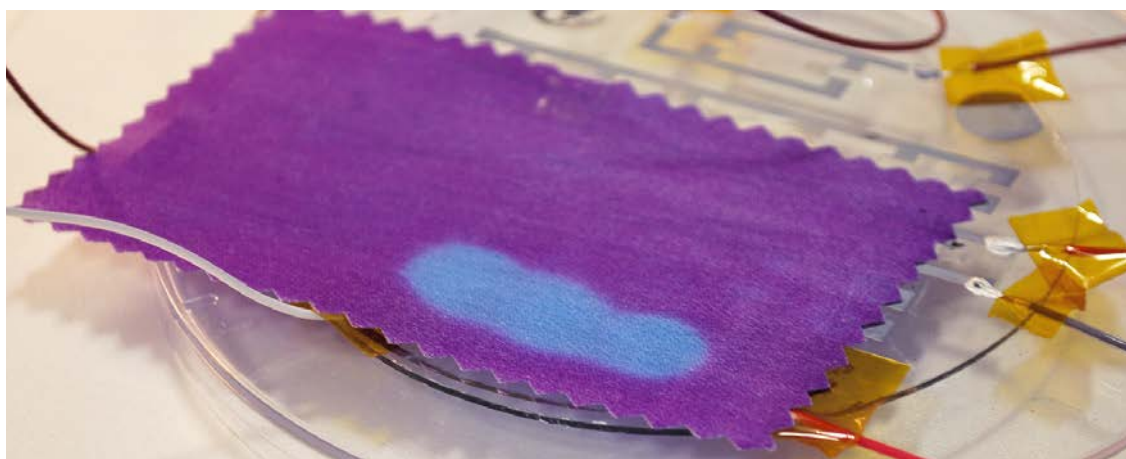


Figure 6.20 Activated areas on a silk-viscose satin fabric, using three active microheaters, from batch 3 and the rigid photovoltaic.

The same set-up successfully demonstrated partial activation using circuit 3 (6 active out of 7 heaters) provided a current and voltage of 0.36A and 0.53V respectively

(0.19W) shortly after the system was turned on, which created some limited activation in areas 1-3 as well as, even more vaguely, in area 6 (see Figure 6.21).

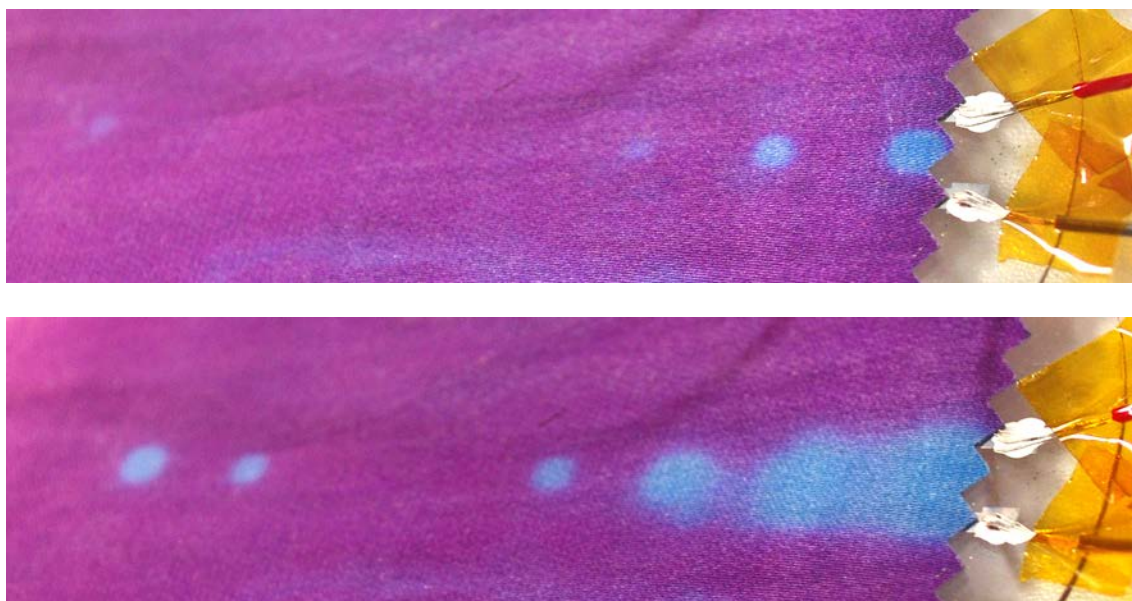


Figure 6.21-6.22 Activated areas on a silk-viscose satin fabric, using 6 active microheaters, from batch 3 and the rigid photovoltaic. Figure 6.21 (top) Note also the vague colour changed circular blue area 6 on the left side of the photo. Figure 6.22 (bottom) The colour changed circles in areas 1-3 in Figure 6.21 have started to morphed into an individual large area.

The activated areas 1 and 2 had started to morph after around another 4 minutes (see Figure 6.22). The tests, however, demonstrated that the activated area did not increase after this time. The samples tested did not change further after an additional 10-15 minutes of exposure time. The set-up with the light box did not create enough power to activate any of the printed samples when connected to a circuit with 9 or more active heaters.

These outcomes positively demonstrated proof of the research concept that the photovoltaic had the potential to convert sunlight into sufficient electrical power in an outdoor set-up to activate the printed thermochromic fabric, especially since the maximum illumination in set-up I (the light box) only produced an average illuminance of 75,000-97,000lux, which is lower than values measured outdoors in sunny sky (90,000-110,000lux). Additional tests were carried out by dimming the light box to 67% (for PV-distant) and 58% (for PV-close) of maximum illumination in order to simulate cloudy sky (between 20,000-35,000lux), to investigate whether the photovoltaic might provide enough power to activate the samples printed with thermochromic dyes under those conditions (see Table 6.6).

Table 6.6 1st and 2nd reading of Current (I), voltage (V) and power (P) when running circuits on glass wafer, batch 3, circuit 1, 3/3 heaters *

Amount of light (dimmer turned up %)	I (A)		V (V)		P (W)	
	1 st reading	2 nd reading	1 st reading	2 nd reading	1 st reading	2 nd reading
75%	0.15	0.25	0.5	0.9	0.08	0.23
83%	0.25	0.25	0.95	1.0	0.24	0.25
92%	0.37	0.37	1.01	1.04	0.37	0.38

* See Table 6.5

The power output when using the settings for cloudy sky condition, set-up I did not provide enough excess heat to activate any of the printed samples that was used within the experiment, which suggests that cloudy sky would probably not provide enough light to power the microheater circuits sufficiently in an outdoor setup. The dimmer was hereafter increased to 75% of the maximum illumination, which produced a power output that measured approximately 0.23W (0.25A and 0.9V), as stated in Table 6.6, when wafer A, circuit 1 (3 out of 3 active heaters) was used. This result only demonstrated a vague indication of activation in areas 1-3, see Figure 6.23.

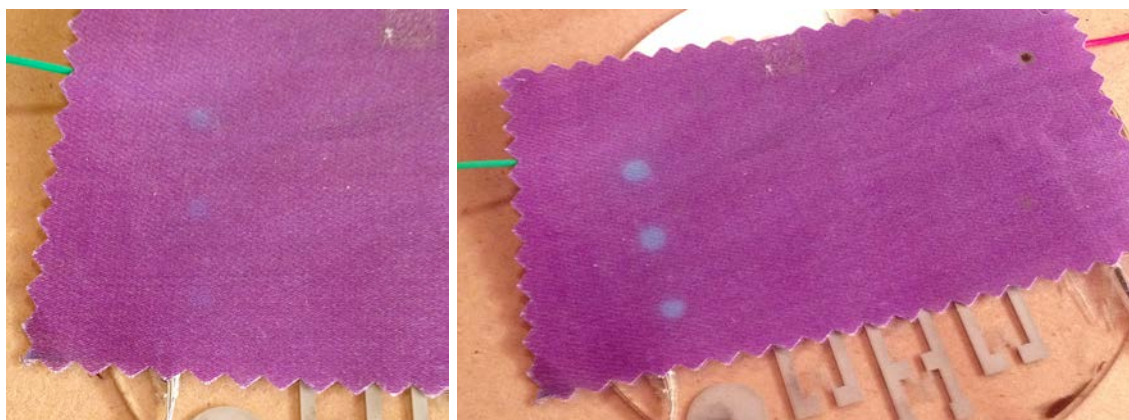


Figure 6.23 (left) The vague activation using circuit 1 (3 active heaters out of 3) during cloudy sky conditions within set-up I (the light box). Figure 6.24 (right) The recorded activation using the same circuit as in Figure 6.23, although with 83% of the maximum illumination (instead of the former 75%).

Furthermore, the limited activation that was observed did not increase even after an additional 10-15 minutes of exposure. However, a clearer colour change was demonstrated when the dimmed lights were increased from 75% to around 80-90% of the maximum illumination. Circles with $\varnothing = 2\text{-}4\text{mm}$ were activated on the silk-viscose satin, which was printed with thermochromic dyes with an activation temperature of 27°C, as the system with the 3 active heaters was set at 83% of the maximum

illumination (see Figure 6.24). The circuits did not, however, provide any further increase even after an additional 10-15 minutes of exposure.

As the illuminance was increased to 92% of the maximum, initial indication of activation was observed on the printed silk-viscose satin, which quickly increased to more prominent circular areas with $\varnothing = 2-4\text{mm}$ (see Figures 6.25). These activated circular areas started to morph after 2-3 minutes and a more solid, approximately rectangular area, measuring around $4 \times 1.7\text{cm}$, was created after 7-8 minutes (see Figures 6.26-6.27). The voltage across the circuit increased marginally to 1.38V after 10 minutes from an initial reading of 1.37V. The surface temperature of the fabric located over the heaters measured 36°C at this point.



Figure 6.25 Initial activation using circuit 1 (3 active heaters out of 3) and set-up I, with a setting at 92% of the maximum illumination.

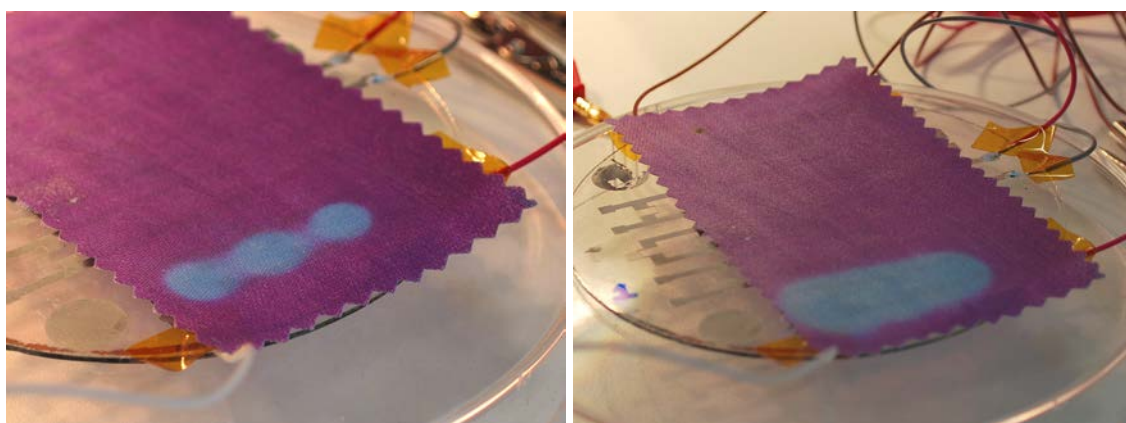


Figure 6.26 (left) The colour changed circles in Figure 6.25 have started to morph into an individual large area. Figure 6.27 (right) The area has morphed and expanded into one large colour-changed area.

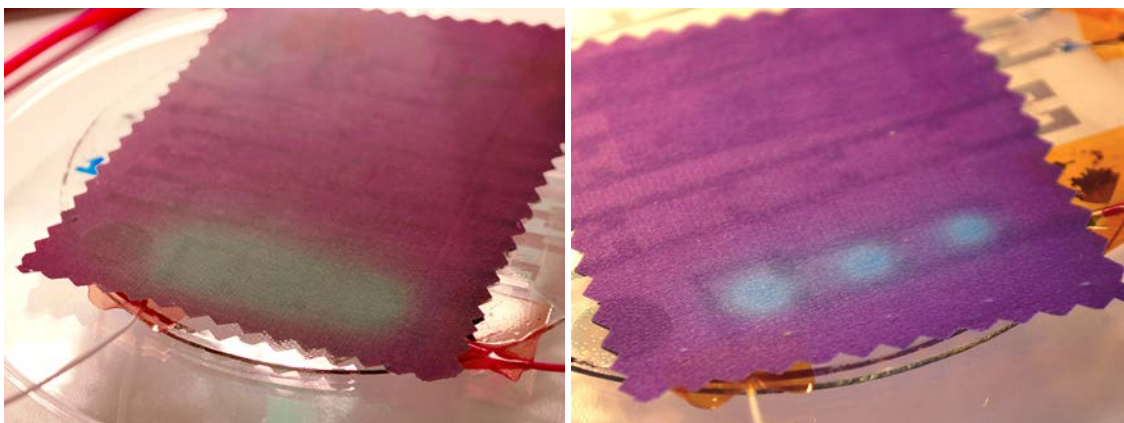


Figure 6.28 (left) Activation using the same parameters as in Figures 6.25-5.27, with the exception of the AT of the sample being 31°C instead of 27°C. Note the larger transitional colour zone around the edges of the colour changed blue area, compared to Figure 6.29 (right) Same as Figure 6.28, with the exception of the AT of the sample being 47°C instead of 31°C.

In addition, the same set-up (previous circuit with 3 active heaters), with illumination strength at 92%, was tested using satin samples printed with the two higher activation temperature dyes (31°C and 47°C). The dye at 31°C resulted in an activated rectangular area measuring roughly 4 x 2cm. However, the transitional area (the area between activated and inactivated areas) was markedly wider, compared to the tests using the dye at 27°C (see Figure 6.28). The sample printed with the dye at 47°C demonstrated the effect of such a high activation temperature as only smaller circles were activated on the fabric (see Figure 6.29).

The experiments with light sources in set-up I demonstrated the potential to use rigid photovoltaics as the power source for activation of thermochromic dyes of activation temperatures up to 47°C, not only in sunny sky but also during conditions of illumination intermediate between sunny and cloudy sky. The experiments conducted also proved that the measurements at the setting PV-distant were more effective as regards the area of activated printed fabric compared to the PV-close setting, because a larger area of the photovoltaic cell was illuminated.

Experiments with the flexible photovoltaic, supplied by Silicon Solar, were carried out with glass wafers (batch 3) and silk-viscose satin samples printed with thermochromic dyes with activation temperature 27°C. It was anticipated that this set-up might demonstrate a less effective result in relation to the area of colour change on the printed samples, due to its lower maximum power output (1.2W), compared with the rigid solar cells (10W). The experiments were conducted to provide a prediction of

whether the flexible photovoltaic might still create enough power outdoors for activation of samples printed with thermochromic dyes. The experiments were conducted with maximum illumination and included tests with both settings, PV-close and PV-distant. However, none of the tests with the flexible photovoltaic proved to be able to produce enough power when illuminated in the light box. Also, circuit 5 (1 active out of 2 heaters), with a power produced of 0.14W (0.2A and 0.7V), did not provide a change in colour. As a result, an additional illuminator (a daylight lamp of 43,000lux) was added to the set-up to see if an improvement in power could be achieved since the sunny sky conditions outdoor measured a higher lux value compared to the simulated value used with the light box. The daylight lamp was, as illustrated in Figure 6.30, mounted covering the front of the light box with the illumination directed on the photovoltaic.

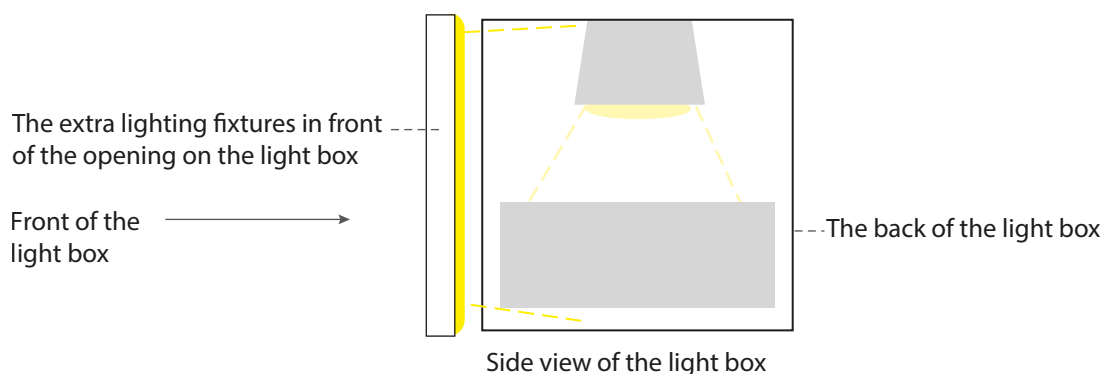


Figure 6.30 Graphic of placement of an extra daylight illuminator in set-up I.

However, the additional light source only generated a marginal increase in power, and no colour change was provided. The question for the outdoor tests thus remains; can the illuminance during sunny sky conditions in set-up J, Graphic 6.2 create enough power for the printed samples to change colour? The likelihood of a markedly different result in terms of colour change, however, is assessed as low given the results from the tests described in this section with set-up I (the light box).

6.1.5 *Activating thermochromic dyes using photovoltaics in combination with heating circuits using outdoor set-up J*

This section demonstrates the success in achieving thermochromic colour change, initiated by the photovoltaic during sunny sky conditions as well as during lux-values intermediate between the defined ranges of sunny and cloudy sky conditions. The investigations within this section, using actual sunlight, were carried out using outdoor set-up J (see Graphic 6.2). The effect of the photovoltaic was, as in previous sections,

analysed using measurements as well as visual observations of the area of colour change on the printed textile samples, in relation to the power output produced as well as illuminance values.

The rigid photovoltaics (Marlec Renewable Power) and the flexible photovoltaic (Silicon Solar) of the outdoor experiments were connected to glass wafers with microheaters from batch 3. For reasons of comparison, the same silk-viscose satin samples printed with thermochromic dyes with activation temperatures of 27°C, 31°C and 47°C from set-up I in section 6.1.4 were also used in this setup. The photovoltaic (alternative 1 in Figure 6.31) was mainly kept horizontal throughout experiments regardless of time of day and date. Currently photovoltaics are most commonly mounted at a fixed angle, or have their angles adjusted two or maybe four times a year. (Landau, 2014) However, a few tests were conducted when the rigid photovoltaic was placed at different angles to the sunlight (alternative 2 in Figure 6.31) with an aim to observe the effect of the angle of the photovoltaic on the power output of the heater.

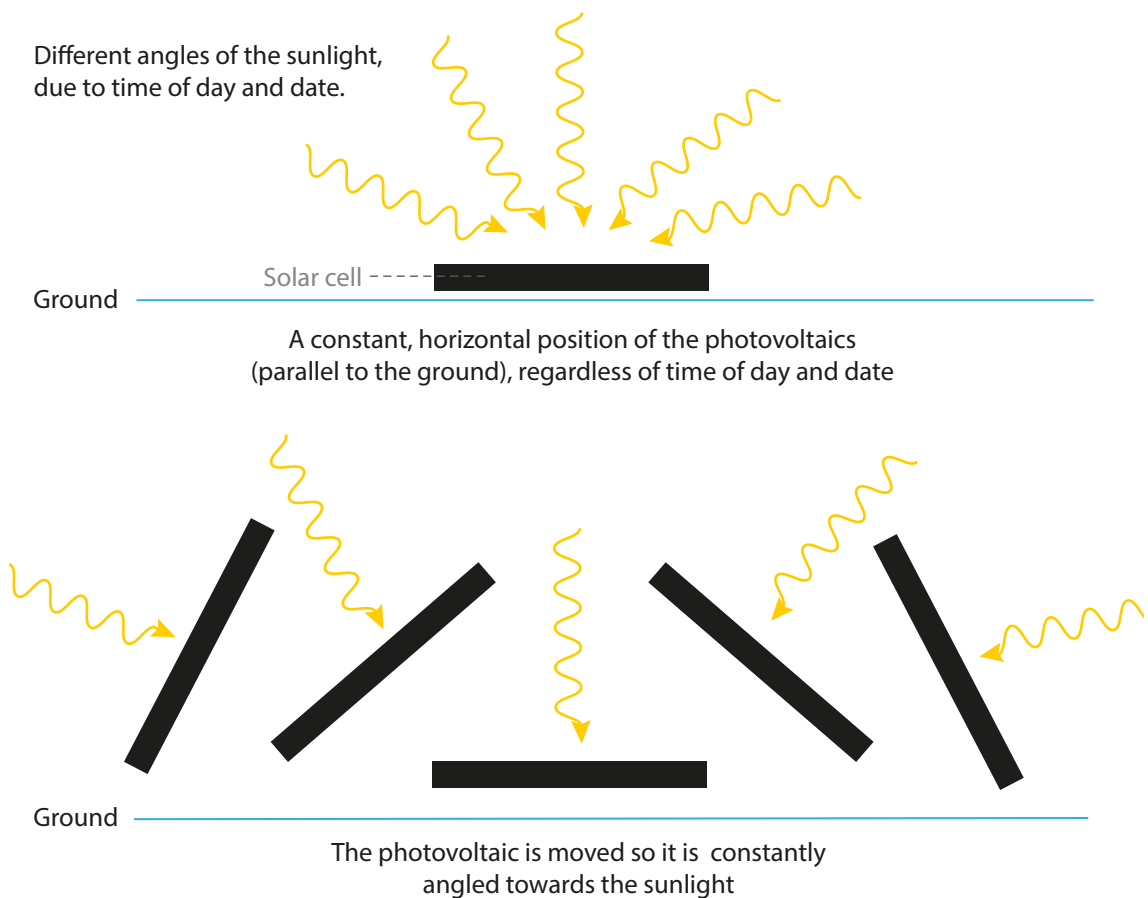


Figure 6.31 Graphic of the two positions of the photovoltaic; horizontal (alternative 1) and angled towards the sunlight (alternative 2).

The difference between set-ups J (outdoors) and I (indoors) is that the outdoor set-up is dependent on wind, which may lower the surface temperatures of the printed fabrics. The experiments were carried out from July to August (the hottest months of the year for the regions of the conducted experiments, see Appendix D) in order to provide maximum effect from illuminance during the different sky conditions. Illuminance values were, as described in section 3.7.1, measured to be in the range 90,000-110,000lux for sunny sky conditions and 20,000-35,000lux for cloudy sky conditions. The ambient temperatures during the test days varied between temperatures in the shade of 22-26°C, which is slightly above the monthly average maximum temperatures for the regions studied (21-22°C) (see Appendix D). The fabric samples were initially placed in direct sunlight during sunny sky conditions. This resulted in direct activation (from the sun's rays) and indirect activation (due to the heat circuits). These samples provided complete activation within 2 minutes because the surface temperature of the entire textile quickly reached 30°C. Henceforth the samples were placed in the shade, while the photovoltaic was kept in direct sunlight (see Figure 6.32).

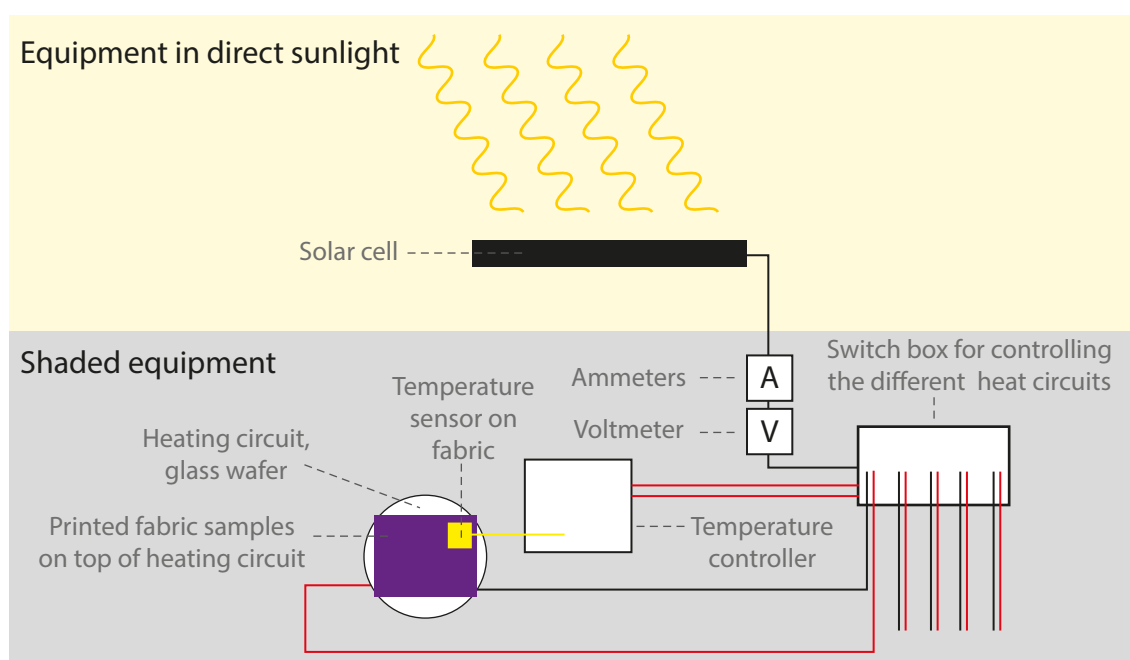


Figure 6.32 Diagram of altered set-up J.

This arrangement meant that the effect of the activation of the printed thermochromic dyes due only to the energy harvested using the solar cells could be studied. However, the shaded ambient temperature and the wind were still factors that affected the results, which is important to note since this sets set-up J (outdoors) apart

from set-up I (indoors). The results from the experiments that are presented in Table 6.7 were carried out on samples in the shade with the photovoltaic in sunlight.

Table 6.7 Current (I), voltage (V) and power (P) when using circuits on a glass wafer (batch 3) connected to rigid photovoltaic.

Sample Set-up (x/y)*	I (A)	V (V)	P (W)	Lux (lux x 10 ⁴)	Activation
27°C silk-viscose satin Circuit 5, 1/2 heaters	< 0.25	< 1.0	< 0.25	3.5-4.0	No
	0.25	1.0	0.25	5.0-8.5	Yes
	0.5	2.0	1.0	8.8-9.0	Yes
	0.5	2.5-2.75	1.25-1.5	10.0-1.10	Yes
27°C silk-viscose satin Circuit 1, 3/3 heaters	< 0.25	< 1.0	< 0.25	3.0-3.9	No
	< 0.25	1.0	< 0.25	4.2	No
	0.25	1.0	0.25	4.8-5.0	Vaguely
	0.35-0.40	1.0	0.35-0.4	6.8-7.0	Yes
	0.48-0.5	1.0	0.48-0.5	7.0-7.2	Yes
	0.48-0.5	2.0	0.96-1.0	8.8-10.2	Yes
27°C silk-viscose satin Circuit 4, 4/5 heaters	0.5	3.0	1.5**	10.0	Yes
27°C silk-viscose satin Circuit 2+5, 6/7 heaters	0.1	1.0	0.1	10.0	No
27°C silk-viscose satin Circuit 3, 7/7 heaters	0.1	0.5	0.05	9.0-9.1	No
	0.25	1.0	0.25	10.0-10.1	Vaguely in area 1
31°C silk-viscose satin Circuit 1, 3/3 heaters	0.48-0.5	2.0	0.96-1.0	10.0-11.0	Yes
47°C silk-viscose satin Circuit 1, 3/3 heaters	0.35-0.40	1.0	0.35-0.4	6.0	No
	0.48-0.5	2.0	0.96-1.0	9.5-10.0	Yes, partly

* The number of active heaters (x) out of the total number (y) within the circuit. The photovoltaic is placed horizontal if no other information is provided.

** Redirecting the photovoltaic directly towards the sun, instead of a horizontal position, see Figure 6.31.

The conclusion from these results in Table 6.7 is that the majority of samples printed with thermochromic dyes with an activation temperature at 27°C tested in combination with the glass wafer circuits, were successfully activated during sunny sky (90,000-110,000 lux) using set-up J. The activated area of the textile on top of two or three active microheaters quickly morphed into an oval shape and the activated area on top of one active heater quickly expanded to a circle with a diameter of 10mm (see Figure 6.33).

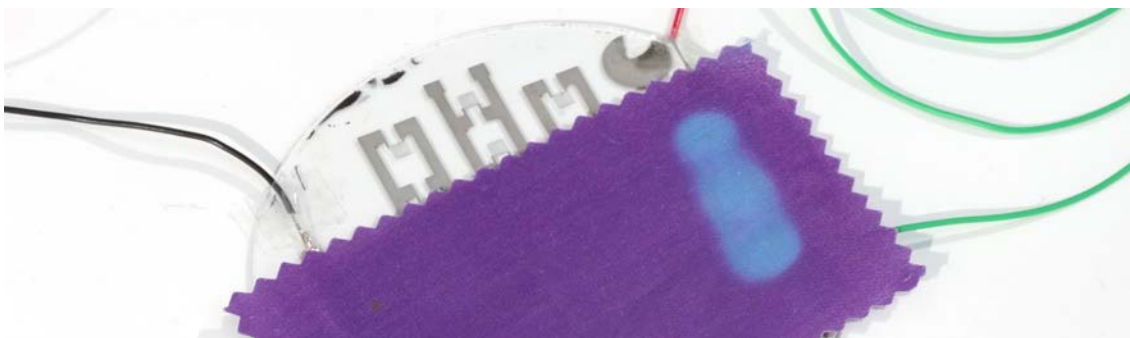


Figure 6.33 Activation using circuit 1 (3 active heaters out of 3) and set-up J.

The circuits with four heaters provided activation when the photovoltaic was redirected towards the sunlight, as illustrated in Figure 6.31, instead of placed in the horizontal position (see Figure 6.34). However, the circuits with six to seven active heaters provided no activation or only vague activation during sunny sky conditions (see Figure 6.35). The heat produced from circuits 1 (3 active heaters) as well as 5 (1 active heater) was enough to successfully activate the printed dye with an activation temperature of 31°C and produce similar results to that for the sample with activation temperature of 27°C (see Table 6.7). The sample with an activation temperature of 47°C only activated a smaller area compared to the samples with lower activation temperatures (see Table 6.7). These results were consistent with the results using set-up I (the light box) in section 6.1.4.



Figure 6.34 (left) Activation using circuit 4 (4 active heaters out of 5) and set-up J. Figure 6.35 (right) Activation using circuit 2 and 4 (6 active heaters out of 11) and set-up J. Note the very vague activation by heater 1 in both of the circuits.

None of the samples were activated during cloudy sky conditions but, as demonstrated using setup I in section 6.1.4, activation did successfully occur for illuminances between the defined ranges of sunny and cloudy sky conditions (see values below 90,000 but above 35,000lux in Table 6.7). Circuit 1 of batch 3 with 3 active heaters created three blue circles

on the fabric with diameter 8-10mm after 2-3 seconds of exposure at illuminances of 68,000-70,000lux. After approximately one minute after the circuit had been connected, the textile surface measured 30.6°C when the morphed oval shape was created. Similar results were observed using circuit 2 of batch 3 with 3 active heaters (see Figure 6.36).

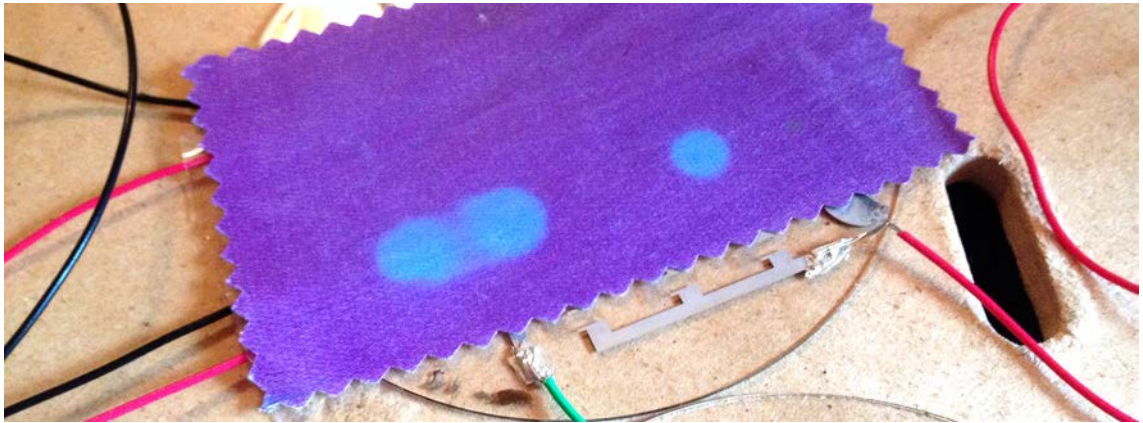


Figure 6.36 Activation using circuit 2 (3 active heaters out of 5) and set-up J. The sample was observed during a sky condition intermediate between sunny and cloudy sky (illuminances of 68,000-70,000lux). Areas 1 and 2 are in the process of morphing into one shape.

6.1.6 *Outcome from experiments using set-up J*

This section presents an analysis of the outcome of the experiments carried out using set-up J, based on the behaviour of the colour change when using outdoor set-up J, compared to indoor set-up I, and also to previous investigations using set-ups A and B. The successful results in this section, both during sunny sky conditions and intermediate sunny and cloudy sky conditions strengthen the proof of concept of using electronic heating devices powered by solar energy harvested by photovoltaics to activate thermochromic dyes. The imagery that was created on the monochromatically printed thermochromic textile was initially circular shapes and, at times, these morphed into larger formations. The particular shapes of the colour changed area was created due to the nature of the construction of the microheaters directly beneath the textile, in combination with the current produced, as well as influenced by the ambient temperature of the textile sample.

The main difference between the test results of set-up J (outdoors) and set-up I (indoors, via the light box) was the behaviour of the time intervals of the colour change, due to the nature of the two light sources. The set-up with the simulated sunlight (I) was set at a constant illumination (the position of the dimmers) and the increase in activation was monitored. The sample proceeded from a period of inactivity (t_2^i) to the

time interval during which the activation increased (t_I^{i-a}), until the colour change had reached the more static changed state (t_2^a) (for an explanation of ‘time intervals’, see section 4.4.2). The outdoor set-up (J) that used actual sunlight as the illuminator provided a more complex colour expression on the printed samples. These samples also passed from an inactive state (t_2^i) to the active state (t_2^a) during a colour changing time interval of t_I^{i-a} . In addition, they reversed from the active to the inactive colour state during the time interval of t_I^{a-i} . The length of the periods of change (t_I) and the more static colour states (t_2) varied depending on the time intervals between sunny and cloudy sky conditions. The activated colour within the samples slowly reversed back to the inactive state when the sky clouded over again (illuminances under 35,000lux). The colour state became re-activated once illuminance levels increased, as the sun came out. This synchronisation between the colour change (activation and inactivation) and the changes between sunny and cloudy sky conditions had previously been observed (see section 4.4.3) during the observations of the printed colour during direct solar activation both indoors on windowpanes (set-up A) and outdoors (set-up B). Set-up J was responsive to natural illumination in the same way that set-ups A and B had been responsive to heat. Compared to the direct solar activation (set-ups A and B), indirect solar activation (set-up J) provided the added possibility, due to the photovoltaic and heaters, to activate the printed thermochromic dyes in less sunlight (illuminance values between those of cloudy and sunny sky condition) instead of full sunlight. Film 7 on the CD-ROM and Figures 6.37-6.48 document the procedure and the colour change created within the sample printed with thermochromic leuco dyes, using set-up J (outdoors) and the rigid photovoltaics, as well as the glass wafer based microheaters. The last section of film 7 as well as Figure 6.47-6.48 demonstrate the synchronised temporal pattern (for an explanation of ‘temporal pattern’, see section 4.4.3) between the colour change (activation and inactivation) and the changes between sunny and cloudy sky conditions.



Figure 6.37 (left) Set-up J. Figure 6.38 (right) Sunny sky conditions. (Photography: Film & Bildstudion AB)

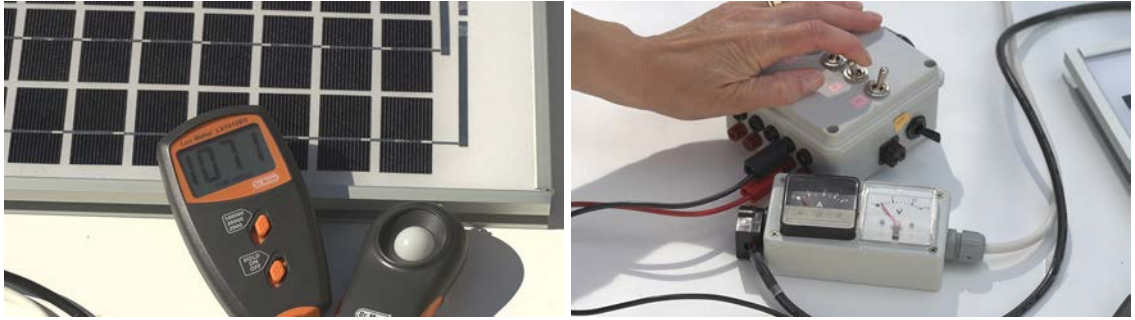


Figure 6.39 (left) The lux value of the sunny sky conditions is measured with a lux-meter. 6.40 (right) The system is turned on, and the voltage produced within the circuit is measured with the voltmeter.

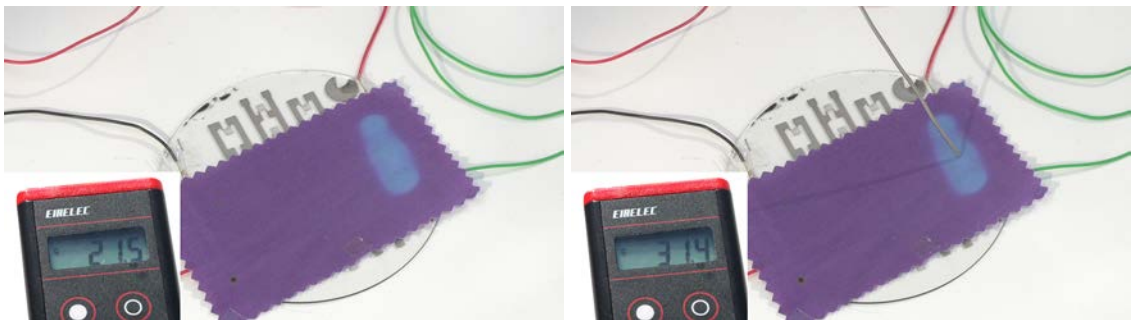


Figure 6.41 (left) Activation of the printed dye. The measured temperature is registering the shaded ambient outdoor temperature. 6.42 (right) The temperature on the surface of the sample in the activated area is measured. The probe is placed on the area of the fabric located over the heater and the registering temperature is at the fabric surface.

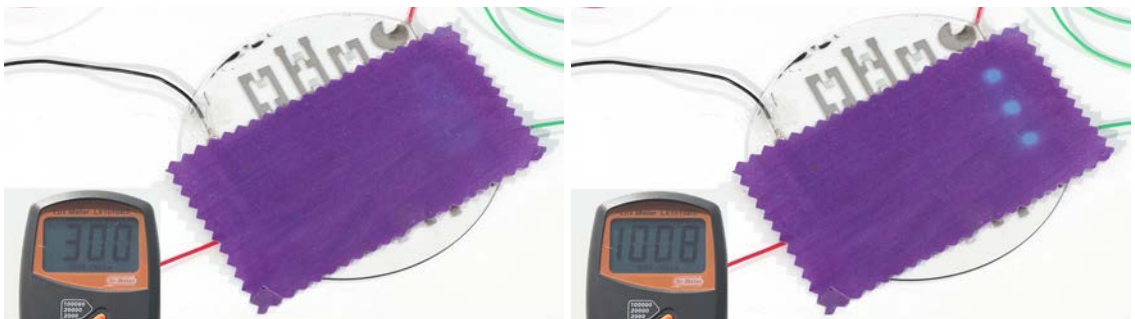


Figure 6.43 (left) No activation, due to cloudy sky conditions. 6.44 (right) Activation, due to sunny sky conditions.

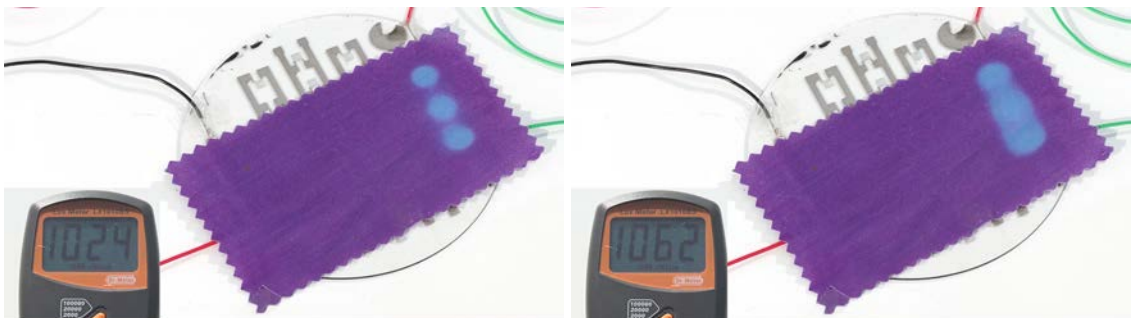


Figure 6.45 (left) The activated area is expanding as the lux value increases. 6.46 (right) The activated areas is morphing into one large active area. (Photography Figures 6.39-6.46: Film & Bildstudion AB)

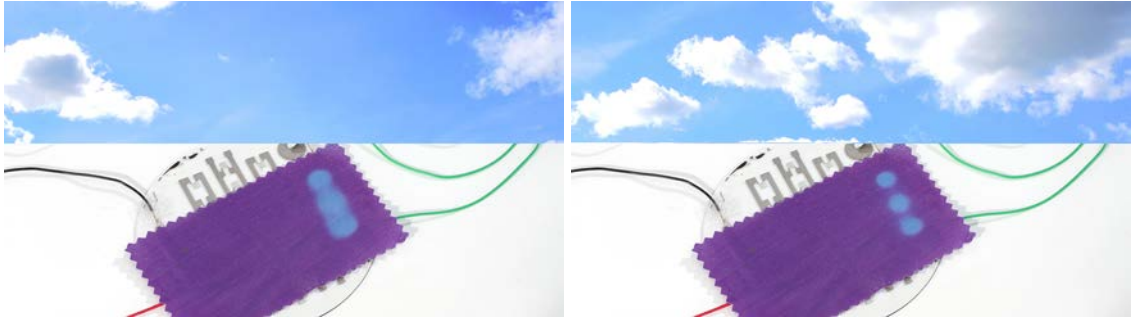


Figure 6.47 (left) The activated area continues to be active as long as sunny sky conditions remain. Figure 6.48 (right) The activated colour within the samples slowly reverse back to an inactive state when the sky is clouded over (illuminances under 35,000lux). The colour change (activation and inactivation) demonstrates a synchronised temporal pattern with the changes between sunny and cloudy sky condition. (Photography Figures 6.47-6.48: Film & Bildstudion AB).

The experiments using setup J and the flexible photovoltaic, supplied by Silicon Solar, were carried out with glass wafers (batch 3) and samples printed with thermochromic dyes with an activation of temperature 27°C. Both circuits 1 (3 active heaters) as well as 5 (1 active heater) were tested. It was, as stated in 6.1.4, anticipated that the activation would be less effective using the flexible photovoltaic compared to the rigid photovoltaic. As described in 6.1.4, the investigation using the flexible photovoltaic and set-up I had proved unsuccessful. The experiments were conducted during sunny sky (90,000-110,000lux) to provide maximum illumination. However, set-up J did succeed to produce a small amount of activation when using circuit 5 (1 active heater), producing a power output of 0.25W during sunny sky conditions (see Figure 6.49).



Figure 6.49 Activation using circuit 5 (1 active heaters out of 2) and set-up J, using the flexible photovoltaic. The sample was observed during sunny sky conditions.

This power output compares with 1.25-1.5W produced with the same set-up (circuit and sky conditions) when the rigid solar cell was used. In comparison, a power

output of 0.25W was obtained using circuit 5 and the rigid photovoltaic for lower illuminances (50,000-85,000lux) than were required to produce this power level using the flexible photovoltaic. It was further noted that the activated area of the colour changed circle on the sample using this setup with the flexible photovoltaic reverted to inactive as soon as the illuminance dropped. The flexible solar cell did not successfully activate the fabric when circuit 1 was tested (3 active heaters).

These observations justified the hypothesis that the flexible photovoltaic would prove to be less effective compared to the rigid photovoltaic. However, the stronger illuminance levels of actual sunny sky, using set-up J, in contrast to the lower value of the simulated sunny sky using set-up I, demonstrates proof of concept to some extent using the flexible solar cell, because partial activation was obtained using circuit 1.

There are several possible areas envisaged for future research, building on the outcomes described in this chapter both from a textile perspective and from an engineering and physics perspective. Investigations in relation to aesthetics, seen from the perspective of a textile designer/researcher, could for example involve possible imageries based on the outcomes of the research described in section 6.1. Other possible future research from the perspective of textile designer/researcher would be the construction of samples with the aim to integrate photovoltaics into textiles printed with thermochromic dyes. Based on the outcomes of this chapter, future research would, regardless of whether from a design or scientific perspective, take an interdisciplinary approach, incorporating not only designers but also engineers and physicists.

6.2 Comparison between activation of printed thermochromic dyes using electrical heating mechanisms powered via photovoltaic, direct solar activation and by ‘traditional’ heat circuitries

The section covers a comparison of the three heating sources (direct and indirect solar activation, as well as ‘traditional’ electrical heating circuits) based on both practical experience and theoretical considerations. The practical features are based on the work that has been described earlier in this chapter on the activation of printed thermochromic dyes using photovoltaics and electrical heating mechanisms (indirect solar activation), as well as in chapter 4 on direct solar activation. The theoretical considerations refer to the information on ‘traditional’ electrical heating circuits presented in sections 2.1.4-2.1.5, including both the author’s prior knowledge and practical experience using ‘traditional’ heating circuits in combination with

thermochromic materials (Ledendal, 2009) and comparable studies reported by other designers. The comparison of the three heating solutions in this section discusses the following design variables; ‘amount of thermal energy’, ‘heating ability’, ‘time interval/temporal pattern’ as well as ‘distribution of heat’ (see section 4.5). In addition, the comparison discusses the descriptors for ‘reversible dynamic patterns’ (see section 4.4.7). This section compares how the design variables and the descriptors relate to the use of photovoltaics and the two other heat sources.

6.2.1 *Design variable: Amount of thermal energy*

The design variable ‘amount of thermal energy’ was defined in section 4.5.1 as the activator’s ability to produce the required temperatures so that the intended thermochromic dye/s will be activate as intended. Activation of printed textiles using solar energy relies on the presence of enough thermal energy through sunlight, as was discussed in design variable ‘amount of sunlight’ in section 4.4.1. The activation of the ‘traditional’ heating circuits, as defined in ‘amount of excess heat’ in section 4.5.1, relies on that enough excess heat (thermal energy) is transferred from the electronic circuit to the printed fabric. The use of photovoltaics changes the sub-description of the design variable ‘amount of thermal energy’, compared to when direct activation as well as ‘traditional’ heaters are used as heating solutions, since the photovoltaics includes a combination of both the sub-variables ‘amount of sunlight’ and the ‘amount of excess heat’. The use of photovoltaics and electrical heating mechanisms places the same demands on excess heat as the ‘traditional’ circuits. The system with the photovoltaic requires sufficient thermal energy to be created via a sufficient amount of illumination through sunlight (‘amount of sunlight’) as the direct activation relies on the solar energy of the sunlight. The successful results in harvesting the sunlight outdoors to power the photovoltaic strengthened the proof of concept of using a more sustainable power source to activate the thermochromic dyes compared to more ‘traditional’ power sources.

6.2.2 *Design variable: Heating ability*

The design variable ‘heating ability’ was defined in section 4.5.2 as the ability of a heat source to provide a specific temperature range in order to activate the chosen activation temperatures of the thermochromic dyes. This parameter becomes of importance if the designer intends to gain control over the colour changes, i.e. when colour stages 1 and 2 are to start and finish, as well as the time interval of the transitional colour phases. As

established previously for the design variable ‘amount of thermal energy’, the heating alternative using photovoltaics is a combination of ‘traditional’ heaters and indirect solar heating. Like direct solar activation, the heating ability of set-up J outdoors (using the photovoltaic) was dependent on the ambient temperature, which in turn is dependent on the geographical location, the time of day and the time of year. However, as with ‘traditional’ heat circuitry, the ‘heating ability’ of the system with the photovoltaic was also dependent on the design of the electrical heating circuit and the materials used in its construction.

The potential for optimisation of the ‘heating ability’ (to provide a more effective colour change) of the system with the photovoltaic could be carried out not only through development and choice of heating circuits as for ‘traditional’ circuitries (described in section 4.5.2) but also through choice of the photovoltaic. Examples of optimisations designed and developed by a textile practitioner and/or through multidisciplinary collaborations have been demonstrated in section 6.1.3. However, the system with photovoltaics provides less control from the textile designer’s perspective compared to ‘traditional’ heating circuitry, because of the random nature of the weather. The efficiency of the set-up has to deal with the factors that cannot be optimised within the physical textile application, such as the amount of illumination due to sky conditions and geographical location of the textile, as discussed in 4.5.2 for direct solar activation.

6.2.3 *Design variable: Time intervals/temporal pattern*

The design variable ‘time interval’ of the thermochromic colour change, as explained in section 4.4.2, defines the time of the transitional colour phase (T) of the colour change ($t_1^{i \rightarrow a}$ and $t_1^{a \rightarrow i}$) and the periods of inactive (t_2^i) and active (t_2^a) colour states. The design variable ‘temporal pattern’ involves a combination of specific lengths of different ‘time intervals’, as defined in section 4.4.3. The possibility to define the start and finish time for heat activation, as well as the possibility to control the speed of colour change is, as defined in section 4.5.3, based on the ability to exert control over the ‘time interval’ and the ‘temporal pattern’ variables. The system with photovoltaics and heat circuitry can of course, just as the ‘traditional’ heating circuitry, be programmed by software to activate and inactivate the set-up as needed. The main barrier to creating defined temporal patterns of colour change, comparing the set-up with photovoltaic and the ‘traditional’ heating circuit, is because of the nature of the weather. The system using photovoltaics will primarily therefore only *actively* activate the printed dye (through turning on the system), during sky conditions that provide enough illumination.

However, an exception to this could be, for example, a system that would store the harvested solar energy in batteries. As described in section 6.1.5, the use of sunlight will lead to a random temporal pattern of the colour change. Therefore, the temporal pattern of the colour change of the set-up with photovoltaics has the potential to follow the rhythms of natural light without the need for software as would be needed with a set-up using ‘traditional’ circuits to simulate the activation.

6.2.4 *Design variable: Distribution of heat*

The design variable ‘distribution of heat’ was defined in section 4.5.4 as the spread of the heat, i.e. the spread of the colour changes due to temperature differences over the textile surface printed with thermochromic dyes. The heat distribution on the printed fabric when using the set-up with the photovoltaic will, as for ‘traditional’ circuits, differ greatly depending on the choice and design of the heat source. However, the colour change will originate from the heaters *and* proceed to spread through the fabric. When using traditional circuits, the distribution of colour change can to a large extent be controlled through design. However, the set-up using photovoltaics will, in addition, have the potential to provide the heat spread through direct solar activation if the printed samples are placed in direct sunlight instead of in the shade. These samples will have the possibility to change colour not only where the heaters are located but also all over the surface, depending on the particular situation. Due to the nature of solar energy, the contact surfaces not only of the actual heating elements, but also of the whole base of the circuit (e.g. the glass wafers in section 6.1.5), can facilitate the heating ability within the printed fabric.

6.2.5 *Definition of descriptors for reversible dynamic patterns*

The descriptor $\{A \ T \ B_i(s^{dt}) \ T \ A\}$ for reversible patterns created with thermochromic dyes for direct solar activation, defined in section 4.4.7, can more or less be used for imageries that are activated through the set-up with photovoltaics, due to the similarity of both situations in involving activation through sunlight. As discussed in sections 4.4.7 and 6.1.5, the colour change of the printed thermochromic imageries, in both direct and indirect solar activation, varies due to the sky conditions (s), the specific date (s^d) and the time of day (s^t). However, the set-up using photovoltaics connected to heating circuitries provides the possibility to create expressions both through choices in different dye activation temperature and decisions regarding the design to provide the activation of different areas of the imagery via the heating elements, as would also be

observed in an application using the ‘traditional’ heat circuitry. Direct solar activation primarily only allows the former. The activated state of reversible imageries using ‘traditional’ heat circuitry is, as defined in section 4.4.7, described by (B) , rather than (B_i) as used for direct solar activation. The activated state of set-ups using photovoltaics and heating circuitry has therefore, like the ‘traditional’ heat circuitry, been defined with (B) only. The descriptor for the set-up using photovoltaics and heating circuitry is, therefore, defined by $\{A\ T\ B(s^{dt})\ T\ A\}$.

6.3 Future design applications that use photovoltaics as a power source to activate thermochromic textiles: predictions through the method of future scenarios

This section contains a discussion, from a design perspective, of the possibilities to develop the research further by integrating the photovoltaic into the textiles. The work in this thesis has demonstrated that sunlight has the potential to provide a more sustainable alternative to induce colour change, compared to the variety of the ‘traditional’ electrical heating mechanisms that have been previously explored (see section 2.1.4-2.1.5). It has been shown that not only direct sunlight, but also indirect sunlight can be used. The experimental work in this chapter was based on applications using rigid or flexible photovoltaic cells that are separate from the textile. The discussion in this section starts by considering the present state of the art in integrating photovoltaics within the textile structure. The method of future scenarios, for definition see section 3.1, is then used based on both the practical experience and the theoretical knowledge gained in this research. Two conceptual solutions are discussed.

The first future scenario, see 6.3.1 for more detail, is a conceptual application in which a sun-screening textile with integrated photovoltaics and heating mechanisms is mounted on the inside of a windowpane. The photovoltaic faces outdoors and the printed thermochromic imagery faces inside. This scenario discusses two possibilities for integrating photovoltaics in textiles, through (a) stitching, or other similar means of attaching, flexible cells and (b) printing photovoltaics on to the textile surface. In this case, the textiles are used as protection from glare or strong sunlight, as discussed in section 2.3, as well as providing an aesthetic trigger through colour change for the people located within the facility. The thermochromic dyes provide the possibility to be activated using solar energy both directly and indirectly. The energy harvested within this conceptual set-up powers the heaters with which the thermochromic dyes can be activated.

The second future scenario, see 6.3.2 for more detail, is a sun-screening concept for outdoor urban textiles. This scenario is based on a set-up where integrated printed photovoltaics are on the sun-facing side of the textile and printed thermochromic dyes are on the other. This scenario is based on the sun sails, which were studied in chapter 5.6-5.7. The textiles provide protection from sunlight as well as an aesthetic trigger through light, shadow and colour play in urban spaces. Compared to scenario 1, the energy harvested may power other devices (lights, electronics, displays, etc.), as well as heaters to activate the thermochromic dyes.

6.3.1 Future scenario 1

It is early in the morning and the sunlight has not yet started to shine blindingly onto the window next to the clerk, sitting by the computer. But at least it is different now. The office last summer was unbearably hot and the blinding light irritated the eyes, making them even more tired after all the hours in front of the screen. The room was warm and sticky, even though the air conditioning was on, due to the strong sunlight shining through the large windows. The room felt clinical with its bright light and white, bare walls.

Midday is approaching, the light outside is peeking through, but it is still pleasantly cool inside. The diffused light from the sun-screening textile on the window is illuminating the room without the glare.

Parts of the surface of the textile facing outside are covered with photovoltaics that are darkly coloured. The heat of the sunlight is partly absorbed by the dark surface at the same time as the solar energy is harvested.

The textile has obtained a new colourway. The heat from the sunlight, and also the photovoltaic cell which has risen in temperature, have directly activated the printed surfaces. The ambience in the room has changed towards a more active mood, leading to a positive working environment in the office.

The sunlight passes behind clouds. Another pattern of printed dye appears within the design, due to the reduction of the direct thermal energy. The new pattern is shaped by the heating circuits, which are powered electrically via the harvested solar energy.

The design alters between different expressions and colourways over the day. The tempo of the changes alters depending on the weather outside, which is creating a more alive

feeling in the indoor environment. There is nothing stuffy about this office anymore.
(Ledendal, 2013-09-05, sketchbook)

6.3.2 Future scenario 2

... It is summer and heat is trapped in the city. Hot, dusty air makes it, at times, nearly impossible to breathe and the sun is burning down on the ground...Light - a lot of bright light... The Calle Siepes⁹ is covered with sun sails. What a relief. No burning sun on your head anymore... Life is pulsing... (Jansen and Ledendal, 2011, p.51)

The laser cut motif within the textiles, creating its light and shadow imageries during the hours of sunlight, appears to move over the facades of the buildings as well as over the street, where people are busy moving about.

The parts of the sun-screening textiles' surface that face the sky are printed with a dark layer of photovoltaics. The energy from the strong sun is harvested via the large textile surfaces that are covering the streets.

The surfaces of the sun-screening textiles, hanging above the citizens, are gradually changing colour when the temperature rises as the day is progressing. The intensity of sunlight, heating the photovoltaic, is speeding up the colour change in the corresponding printed areas on the other side of the textile, thus creating a temporal pattern with sections of colour-changed areas on the printed textiles. The hues of the active colours in the textiles are intensifying the busy tempo on the street below, accentuating the energy that is flowing through the areas of boutiques and cafés. It is afternoon - the textiles shift in colour a second time as the temperature in the street rises. Later the more quiet colouring from the morning is yet again visible as the sun is setting and the ambient temperature has dropped.

The air is starting to cool down and the evening activities in the street are slowly taking over. Ambience is created from the lit streetlights, which are powered by solar energy stored from the energy harvested, earlier that day, from the photovoltaics that cover the sun-screening textiles hanging over the street.

(Ledendal, 2013-09-13, sketchbook)

⁹ An area of Seville.

6.3.3 *The potential of incorporated photovoltaics as illustrated in the future scenarios*

This section discusses two future scenarios, based on the findings of the research described in this thesis as well as documented reports by other researchers within the areas of photovoltaics and textiles. The section elaborates both on what is currently feasible and on novel possibilities for the future. The prospects for creating the dynamic sun-screening products as depicted in the two future scenarios depend not only on direct sunlight activation but also on research required to integrate photovoltaics within the textile structures. This section debates the latter concept. Proof of the concept of direct sun activation has been provided through the research described earlier in this chapter. A first step in proving the concept to use integrated photovoltaics as the energy supply for a heating mechanism that activates printed thermochromics was provided in section 6.1.4-6.1.5, where both rigid and flexible photovoltaics were used successfully, although not integrated. The possibilities predicted for the next step, i.e., using integrated photovoltaics as the energy supply, are discussed as follows.

Future scenario 1 presents two technical possibilities for integration; stitched flexible solar cells *or* printed photovoltaics. In such applications, flexible photovoltaics would be preferred over rigid cells for integration due to the flexibility properties of textiles. It is likely that flexible photovoltaics combined with a textile printed with thermochromic dyes, integrated, for example, by stitching the flexible photovoltaics to a textile structure is feasible. Several applications with flexible photovoltaics stitched onto the textile have been presented and discussed at conferences and in papers since 2000. There are also conceptual prototypes and products launched on the market, which contain integrated photovoltaics, for example, on garments, bags and other accessories. Examples of such products presented in section 2.3.3, are ‘the Ecotech Solar Jacket’, the ‘Solar Vintage’ products and the ‘Solar bikini’. (Schubert and Werner, 2006; Schneider, 2007; Seymour, 2008; Talk2myShirt, 2009; Corchero, 2010) The stitched photovoltaics in these examples operate LEDs as well as electronic devices such as iPods and laptops, rather than as activators for printed thermochromic dyes. However, these examples demonstrate the feasibility of stitching the photovoltaic to a textile fabric while retaining the ability to harvest and then transfer the energy.

Initial experiments, within this thesis, that integrated flexible photovoltaics with the textile structure through gluing the cell onto the fabric, were carried out. Four

samples were printed combining dyes with activation temperatures of 27°C and 31°C on silk-viscose satin and devoré-printed silk-viscose velvet. The flexible photovoltaics were mounted so that they partially covered the printed samples to observe the effect on the activation of the thermochromic dyes. The photovoltaic was placed between the fabric and the windowpane (see Figure 6.50). The printed thermochromic dye demonstrated faster activation in the areas in contact with the photovoltaic, compared to the windowpane, indicating that the photovoltaic cell acted as an indirect source of heat, after it was heated directly by sunlight. This provided design-related impact on the ‘the contact surface’ design variable, as defined in section 4.4.4. An aesthetic effect of the increased rate of colour change in areas of the printed structure in contact with the photovoltaic, due to the integrated photovoltaic compared to direct sun activation, is described in future scenario 2 in the sentence ‘creating a temporal pattern with sections of colour changed areas on the overall printed textiles’. (Ledendal, 2013-09-13, sketchbook)

The heat-spread, demonstrated by the colour change of the four printed samples investigated, originated from the areas in contact with the photovoltaic and then spread throughout the printed samples. The activated imagery on the textile surface initially took the shape of the photovoltaic, before all-over activation, (see Figures 6.51-6.52).

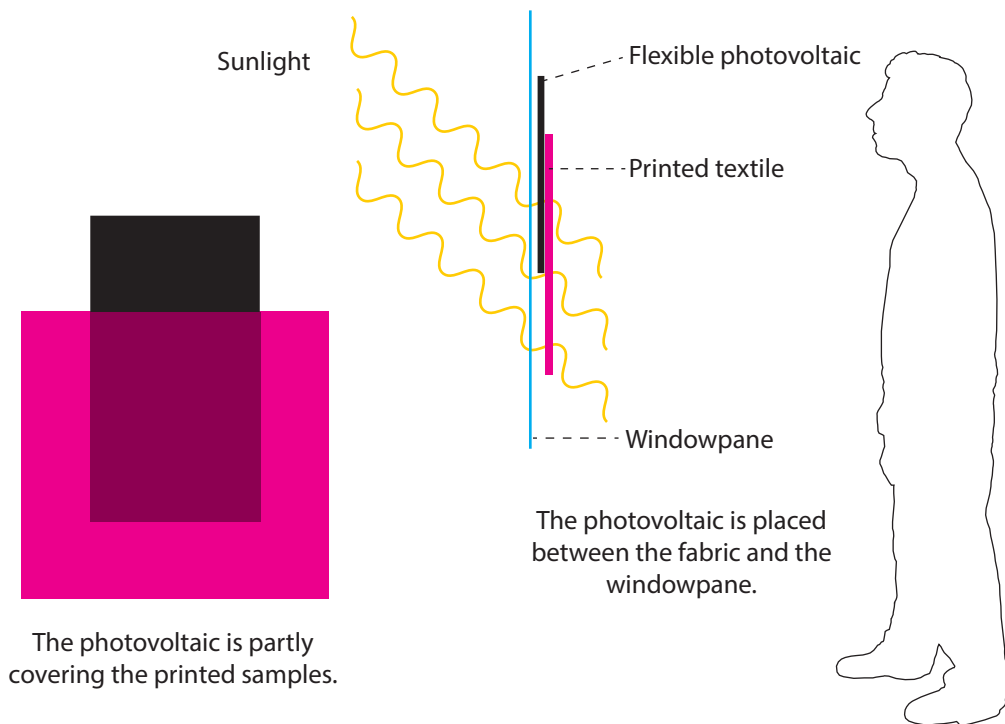


Figure 6.50 The placement of the photovoltaic in observation set-up A.

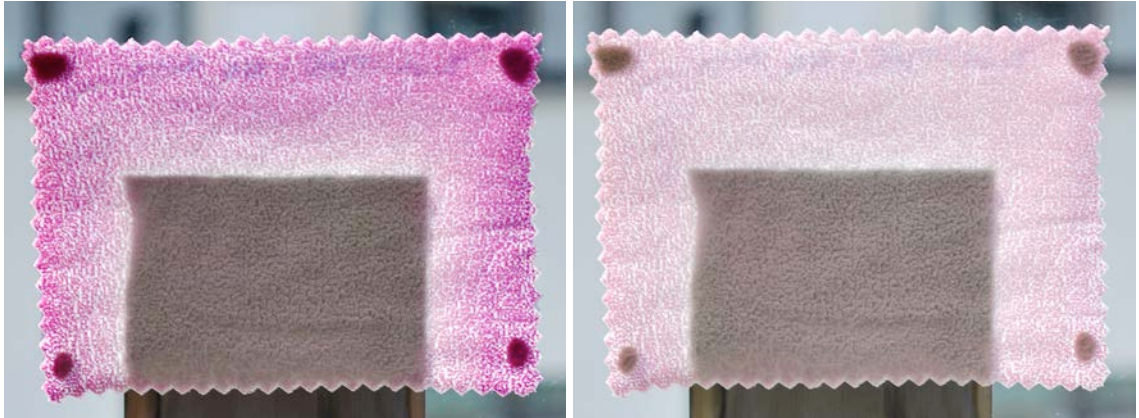


Figure 6.51 (left) The activated area on the sample initially takes the shape of the photovoltaic. Figure 6.52 (right) Thereafter, the entire sample is activated.

Similar indirect heating effects have previously been described in this thesis, for example, on printed textile surfaces during direct sunlight activation scenarios when samples were mounted on windowpanes (see section 4.4.4). However, the photovoltaic proved to be an even more effective heater than the window. Measurements, using an Eirelec E5000 microprocessor controlled handheld thermometer, demonstrated the increased temperature of the photovoltaic, compared to the windowpane. The thermometer probe was placed at the five following places: (a) 1cm from the windowpane, (b) on the windowpane next to the sample, (c) on the photovoltaic, (d) on the area of the sample in contact with the photovoltaic and (e) on the area of the sample with no photovoltaic behind (see Figure 6.53).

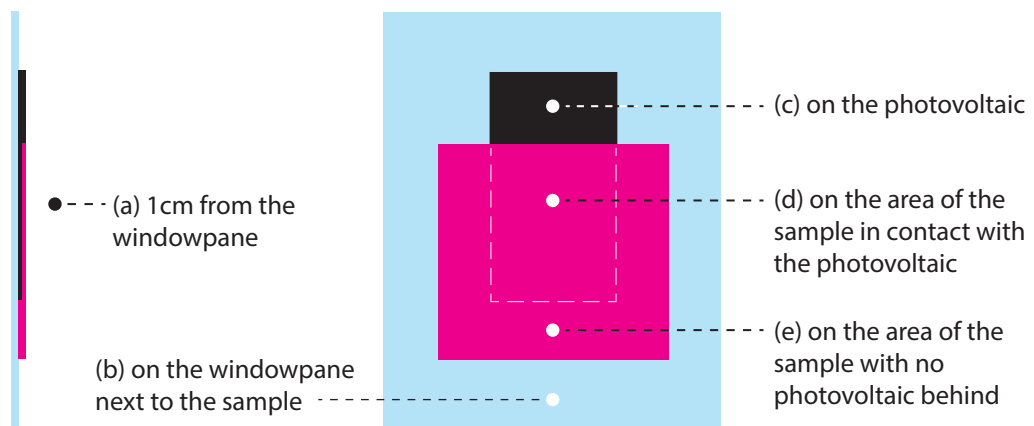
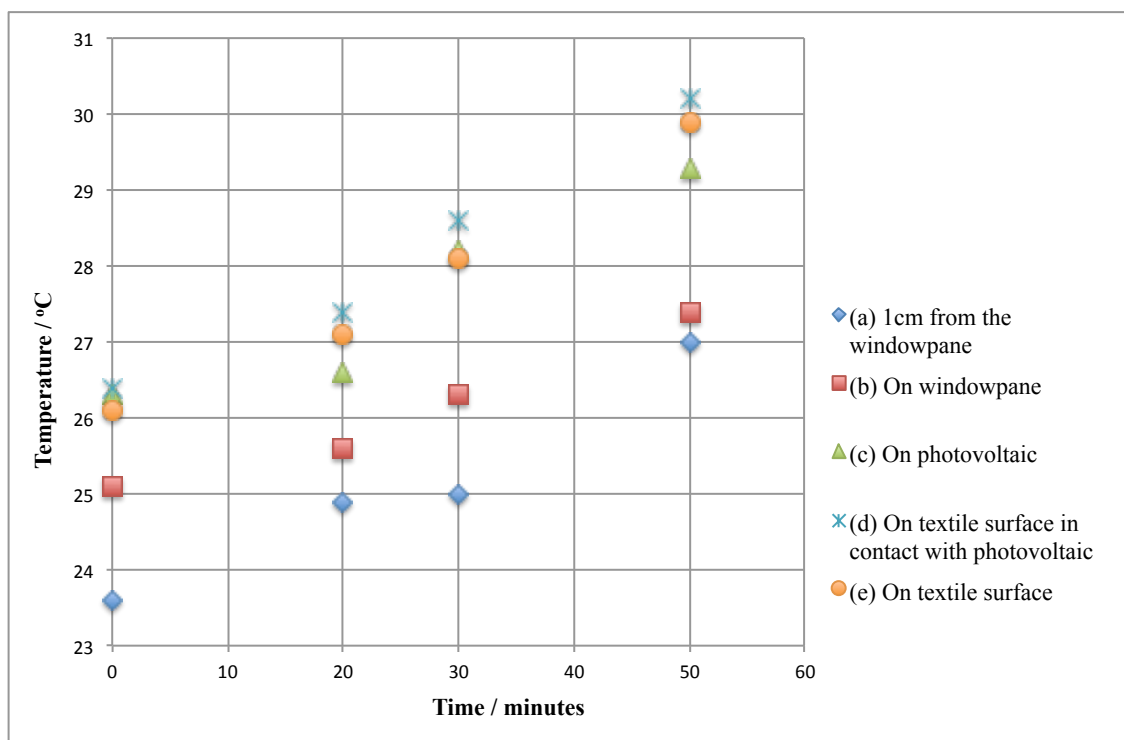


Figure 6.53 The placements of the thermometer probe.



Graph 6.1 Temperature curves for set-up A for test with photovoltaic.

The data given above were collected during sunny sky conditions on September 3rd 2012 for a silk-viscose satin sample printed with thermochromic dyes with an activation temperature of 27°C. The initial temperatures were measured when the sunlight first shone on the printed samples (time 0 in Graph 6.1), when no activation had occurred. Three measurements were then taken at 20, 30 and 50 minutes after the initial measurements. After 50 minutes, the sample had acquired complete all-over activation. The measurements demonstrate that the temperature of the parts of the fabric that were in direct contact with the photovoltaic were marginally higher than the parts which were in contact only with the windowpane (see Graph 6.1). This is likely to be due to absorption of additional energy by the dark surface of the photovoltaic.

The prospects for using flexible photovoltaics integrated with textiles printed with thermochromic dyes are bright also for the following reason. Results presented within this thesis have demonstrated that it is possible to use solar energy, harvested by non-integrated photovoltaics, to activate the dye via microheaters. The results using set-up J (outdoor) were not as effective with flexible as with rigid photovoltaics, see section 6.1.5. However, the commercial cells used have lower efficiency levels compared to the latest cells reported in laboratory studies. It is hypothesised that the power output of flexible (and rigid) solar cells will improve in the future due to continuing technical

developments. In 2008, the theoretical efficiency for the first-generation of silicon photovoltaics was predicted to be around 29%. The reported optimum laboratory efficiency level, at the time, was around 25%. (Science Daily, 2008) The predicted theoretical efficiency was dramatically revised in 2013, due to the new results presented by the Fraunhofer Institute for Solar Energy Systems ISE, Soitec, CEA-Leti and the Helmholtz Center Berlin with their new concentrator photovoltaics (CPV) with an efficiency level of 44.7%. The CPVs were reported to achieve more than twice the efficiency of conventional photovoltaics. (Fraunhofer ISE, 2013) These recent results demonstrate the remarkable changes that this field is still undergoing. Additionally, the intense importance placed on the future of solar energy conversion for society globally may provide new breakthroughs and decisive developments within this field, which in conclusion provide good prospects for practical use of integrated solar cells in textile applications in the future.

The concept in future scenario 2 (as well as the second technical possibility for integration in scenario 1) involving printed photovoltaics appears to be slightly further away than attaching flexible photovoltaics to the textile surface at present. Research has been carried out for a number of years into this field and is ongoing, so the prospects for such applications are still within reach. (Krebs et al., 2005; Sommer-Larsen, Damgaard Nielsen and Krebs, 2008; Henderson, 2009; Wilson, 2012; RISØ DTU, n.d.a) In section 2.3.3, RISØ DTU is provided as an example of a company with a research team that works with printed photovoltaics and has published information on printing photovoltaic technology onto textiles. (Henderson, 2009) Krebs et al. (2005), have presented two different prototypes where the use of polymer photovoltaics printed onto clothing has been investigated, see Figures 2.54-2.57 for one of the examples. The first alternative resulted in a surface structure by adding a material layer based on directly incorporating a polymer photovoltaic on a polyethylene terephthalate (PET) substrate. The second alternative, a photovoltaic fully integrated into the textile, was created by laminating a thin layer of polyethylene (PE) onto a textile material. The textile was then plasma treated to create a PEDOT electrode. After the active material was screen-printed the other electrode was created by evaporation. The former prototype was tested on a transparent plastic substrate, creating a rather rigid foil. The foil had a clear red colour due to the coated electroactive polymer material. Because of the stiffness of the foil material, the latter prototype focused on creating the solar cell

within the textile structure, retaining the flexible structure of a textile. Application of a layer of PEDOT, gave a blue tone and the screen-printed active polymer became red. The efficiency of the photovoltaic on the PET substrate was similar to that of other previously published screen-printed results. The integrated version showed a rather short lifespan and best results were obtained with a newly constructed cell. The material degraded when illuminated by the sun, reportedly due to lack of oxygen barriers. (Krebs et al., 2005, p.1-6)

The work at the Massachusetts Institute of Technology (MIT) by the research team of Karen Gleason is another example of printed photovoltaics, which have been successfully printed onto fabric. The MIT solar cells are reported to be low-cost and have also been successfully printed onto untreated paper and plastics. These photovoltaics were printed using a process that uses vapour, rather than liquids, at a temperature between 20 and 100°C. The printed paper substrates, as well as plastic photovoltaics, have proved to function after being folded up to 1000 times, without significant loss in efficiency. In addition, the cells printed on paper withstood application of a laser printed ink layer on top of the photovoltaics, as well as a laminated coating to withstand outdoor exposure. (Barr et al., 2011, pp.3500-3505; Chandler, 2011)

A third example that, at the process level, is similar to printing is a collaborative project between Power Textiles and Heriot-Watt University, where research into the deposition of thin silicon films onto woven polyester fabrics has been conducted. Wilson, Lind and Mather have been working on creating a more flexible system, by building up the photovoltaic cell onto polyester textiles using a plasma unit with a gas/vacuum process to deposit the n-i-p silicone layers. The semiconductive layer has a brown colour and when bonded well it has a consistency of a very thin 'metal coating'. Functional issues demanded flatness in the structure of the textile substrate explaining why a plain weave was used. The material was pre-treated by slightly levelling off to improve the flatness of the structure. After stabilising the woven textile through a pre-treatment, which created a dark green layer on top of the substrate, the surfaces were coated with an aluminium layer, which created a silver finish. On top, to provide a contact, a shaped sputtered aluminium layer, was added. At the present state of development the material is rather rigid, which is believed to be associated with moisture evaporation during the coating process. However, the material is more flexible than current commercial thin film cells. (Wilson, 2012; Lind 2013)

The efficiencies of all of the examples given above of novel photovoltaics are currently lower than generally-available commercial photovoltaics. The printed photovoltaic of RISØ DTU has, however, a proven efficiency level of 5.9% and has been successfully used in lighting applications. The printed MIT cells have been reported with an efficiency level of 1%. (Sommer-Larsen, Damgaard Nielsen and Krebs, 2008; Wilson, 2012; Lind, 2013)

The energy harvested from these textiles has not yet been used to activate textiles printed with thermochromic dyes. However, the possibilities of using examples such as those from the MIT or the RISØ DTU laboratories potentially offers a more seamless integration between the photovoltaic and the thermochromic textile, compared to attached flexible cells. This is because the printed surface becomes much more ‘at one with the textile structure’, as with traditionally printed material, rather than an additional film that is stitched on top of, or between, textile layers. Furthermore, the foldability of the paper photovoltaics produced by MIT provides interesting prospects for greater flexibility resembling that of normal cloth, compared with current commercial photovoltaics. From the textile design perspective of the author, this feature appears very interesting for future textile applications of integrated photovoltaics.

Furthermore, the printed photovoltaics provide the possibility for freer imagery-related design aspects. The printed flower-shaped photovoltaics, in the clothing design created by Hertz and RISØ DTU (see Figures 2.55-2.57) are shaped from smaller photovoltaic elements within the imagery, compared to the larger solid shapes in, for example, Corchero’s solar fan created by stitching (see Figures 2.52-2.53). From the point of view of the author’s industry knowledge as a designer, the latter alternative would most likely be more restrictive for the expression of the imagery, because of the requirement for pre-shaping of the flexible cells. (Seymour, 2008, p.46; RISØ DTU, n.d.b and n.d.c) The additional possibility, as with the MIT cells, of added motif and coloured layers on the photovoltaic surface and the outdoor protection opens up new and interesting design aspects.

The prediction therefore is that the future looks promising regarding new design challenges and design opportunities for photovoltaics integrated in textiles, as exemplified by the applications suggested in the future scenarios described in this section. Of course, this will be dependent on several factors, such as whether research into photovoltaics will continue to provide new development as it has over the last two

decades. It is also important that collaborations between designers and scientists, such as the example of RISØ DTU and Wingfield/Loop.pH given in section 2.3.3, will continue to be established with the resulting collaborative platform acting as a catalyst for the development of photovoltaics integrated into textiles.

Chapter 7 Conclusions

This doctoral thesis has focused on using sunlight, uncontrollable by nature, to create a dynamic colour change by activating thermochromic leuco dyes within textile applications. The thesis has investigated the potential to use the sun as the sole activator, either directly (sunlight is directly incident on the textile application) or indirectly (the sun is incident on photovoltaic solar cells in order to generate electricity that, in turn, activates the dyes). The research described in chapters 4 to 6 has resulted in a set of guidelines to expand the aesthetic vocabulary for textile printmaker practitioners to reduce the complexity when working with textiles using thermochromic dyes. The intention is that the findings will strengthen and facilitate the exploration and use of thermochromic dyes in design applications. Some of these guidelines may also be used when working with textile applications that utilize the presence of sunlight by creating designs for a three-dimensional space, in which the textiles are located, producing dynamic effects of light and shadow imageries and light qualities within that space.

In the context of using uncontrollable sunlight as the dynamic activator, controlling the aesthetics of the thermochromic dyes may appear less straightforward compared to when using other activators. Similar lack of control may be present for the projected light and shadow imageries that are created due to the interaction between the physical textile and sunlight. This concluding chapter compares the complexity in the design applications of dynamic thermochromic dyes that are activated with sunlight with three other textile print applications. The analysis demonstrates the increase in complexity, as well as where in the design process this occurs, not only when using dynamic dyes but also when textiles are back-illuminated by sunlight. The outcome of the analysis presents suggestions for how to provide greater control, when possible, to define the aesthetic result in these more dynamic design applications. Naturally, however, a designer or artist will never be able to exert full control of a design. The viewer's subjective experience will always be influenced by the context of the artefact. The discussion within this chapter is, therefore, focused on the designers' ability to define the aesthetic outcome of the textile applications in relation to choice of colour and design, materials and construction techniques. The four types of design applications that are described in this chapter are illustrated using four schematic diagrams (see diagrams I-IV). The schematic diagrams describe the level of

controllability (either ‘controllable’, ‘partly controllable’ or ‘uncontrollable’) of the four types of textile applications, with the aim to clarify the printmaker practitioners’ ability to control the aesthetic outcome within the applications. A designer’s ability to control a design application with dynamic performance is contrasted with the ability to control the aesthetics of a ‘traditional’ textile (textiles printed with non-dynamic materials). Comparisons are also made between using ‘traditional’ heating solutions to activate thermochromic dyes and using the sun as the source of heat. Compared with using traditional heating mechanisms, which only provide a two-dimensional aesthetic, using sunlight as an activator provides the opportunity to create a three-dimensional aesthetic – defined within this thesis as ‘the extended imagery’.

Additionally, this chapter presents a discussion of the extent to which this thesis presents more environmentally sustainable solutions for activating thermochromic dyes, compared to current solutions within the field of knowledge of thermochromic design applications (for example, as presented in section 2.1.4). Finally, this chapter provides possible ideas for future research that build on the work presented within this thesis.

7.1 Schematic diagrams visualising the design process

This section provides a comparison of the possibilities for the textile printmaker practitioner to control the aesthetic outcome of four types of textile design applications. The comparison is based on the level of complexity, which is illustrated by four schematic diagrams, one for each of the four types of textile applications. In addition, this section presents a discussion on how to increase the controllability of the aesthetic results from three of the types of applications.

The author has compiled these four explanatory diagrams based on the tacit knowledge accumulated from years as a printmaker practitioner, combined with the experimental outcomes from the work of this thesis. The schematic diagrams I to IV, see Figures 7.3-7.6, are based on the following five types of textile products (i)-(v):

- (i) ‘Traditional’ textile products that are free-hanging and penetrated by sunlight;
- (ii) ‘Traditional’ textile products that have a solid surface located behind the textile.

- (iii) Printed smart textiles, using a ‘traditional’ heating solution to activate thermochromic dyes;
- (iv) Textiles printed with thermochromic dyes that use sunlight as a direct activator;
- (v) Textiles printed with thermochromic dyes that use sunlight as an indirect activator.

The schematic diagrams are organised into two pairs, based on the following two parameters (for method see section 3.2.3):

- a) Dynamic materials versus non-dynamic materials;
- b) Back-illuminated textiles versus non-back-illuminated textiles.

The following four types of applications (I-IV below), represented respectively by schematic diagrams I to IV, which are based on the five types of textile products (i)-(v), are established by combining the two pairs of parameters (a) and (b) (see Figure 7.1);

- I. Non-back-illuminated textiles printed using only non-dynamic dyes/pigments (ii)
- II. Non-back-illuminated textiles printed completely/partially using dynamic dyes (iii), (v)
- III. Back-illuminated textiles printed using only non-dynamic dyes/pigments (i)
- IV. Back-illuminated textiles printed completely/partially using dynamic dyes (iv), (v).





	Parameters of investigation			
				
I		×		×
II	×			×
III		×	×	
IV	×		×	

Figure 7.1 The four types of applications formed from the two pairs of parameters.

The four schematic diagrams, I to IV, provide a general overview of the level of complexity of the four types of design applications, because it is not feasible to take every possible design outcome into consideration. For a specific design application, a tailor-made diagram may be devised. The collaborative work with Barbara Jansen, PhD student at University of Borås, Sweden, in section 5.6.3, discussing the ability to use

two particular design solutions for sun-sails covering a street in Seville, Spain, is an example of such a specific design application.

The schematic diagrams have been divided into four levels, as illustrated in Figure 7.2, aiming to clarify the printmaker practitioners' ability to control the aesthetic outcome within the four types of textile applications (I-IV).

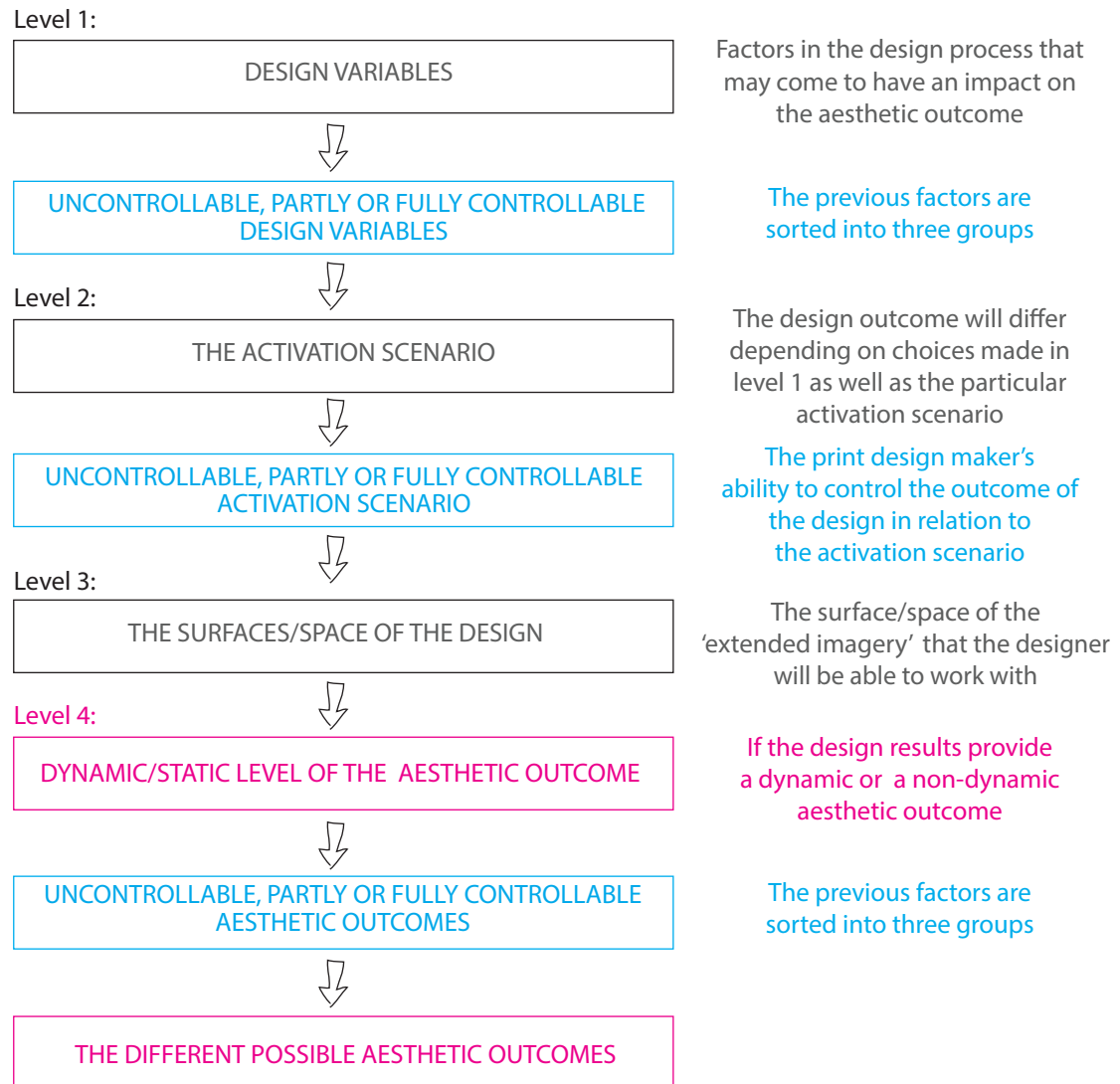


Figure 7.2 Overall structure of the schematic diagrams.

The first level in the diagram represents the different design variables that result in an impact on the final aesthetic outcome (see black text, level 1, Figure 7.2). The design variables are affected both by external factors (such as sky conditions, time/day/year) and textile-related factors (such as the choice of dyes/pigments, colours, textile materials, printmaker techniques). In the cyan text, level 1, Figure 7.2, these factors are sorted according to the level of controllability that the printmaker

practitioner might have over particular design variables; assessed as ‘controllable design variable’, ‘partly controllable design variable’ and ‘uncontrollable design variable’. This sorting might differ for individual design applications, but since it is the overall structure of a type of design application that is of interest, individual differences have not been brought into this part of the evaluation.

Level 2 describes the chosen solution of activation of the dynamic dyes, when these are used (see black text, level 2, Figure 7.2). The design outcome will differ depending on the printmaker practitioner’s choices made in the previous level as well as the particular activation scenario. These factors are also sorted into groups as to the extent of control the printmaker practitioner might have over the activation scenario; ‘controllable activation scenario’, ‘partly controllable activation scenario’ and ‘uncontrollable activation scenario’ (see cyan text, level 2, Figure 7.2).

Level 3 deals with the complexity of the surfaces within the space in which the printmaker practitioner is working (see level 3, Figure 7.2). Certain diagrams are only limited to the more ‘traditional’ two-dimensional surface (the textile), while others also includes the spatial arrangement of the ‘extended imagery’ (‘the incident surfaces’ and ‘the intermediate zone’). If the design outcome includes all the components of the ‘extended imagery’, then the design process becomes more complex.

Level 4 concerns the design result. The options in this level are whether the aesthetic outcomes have a dynamic content or if they are non-dynamic, as well as the infinite number of possible design results of the intended artefact (see magenta text, level 4, Figure 7.2). The parts within the design that have a dynamic outcome, the parts that are non-dynamic, and the combination of both can vary from design to design. An aesthetic dynamic outcome within the sub-levels of ‘the extended imagery’ does not necessarily mean that a dynamic dye has been used within the design, since dynamic aesthetic change can take place in light and shadow patterns displayed on ‘the incident surfaces’ or through the quality of the light in ‘the intermediate zone’ (for an example see section 5.8). Dynamic changes were also observed *on* the textile in coloured surfaces printed only with non-dynamic dyes/pigments, defined within this thesis as ‘traditional’. An example of this last effect is the colour change that occurred when a viewer moved around the silk-viscose velvet textile, as described in section 4.2. The controllability of the dynamic and non-dynamic outcomes can vary between ‘controllable design result’, ‘partly controllable design result’ and ‘uncontrollable

design result' (see cyan text, level 4, Figure 7.2). A 'controllable design result' refers to an aesthetic outcome that the print design maker can more or less fully define, meaning that the intended outcome would be more or less what the viewer/user would perceive. A 'non-controllable design result' refers to the opposite, meaning that the designer can expect very little control over how the design will be perceived by the viewer/user, in relation to how the designer created it. A 'partly controllable design result' includes aspects of the aesthetic outcome that the designer can define as well as parts that are beyond the designer's control. The degree of control in defining the aesthetics varies between different specific design applications. The definition given above disregards subjective qualities such as whether the design is liked or disliked. Rather, the definition refers to the designer's ability to oversee the control of aesthetics such as shape, colour, motif, material etc.

7.1.1 *The non-back-illuminated textiles*

This section explains schematic diagrams I and II, which represent textile applications that include non-back-illuminated textiles. Schematic diagram II, additionally, includes colour dynamic materials, e.g. thermochromic dyes.

Schematic diagram I, Figure 7.3, illustrates the simplest option of the four types of applications. This diagram describes non-back-illuminated textiles using non-dynamic dyes. The type of application is based on the more 'traditional' way of approaching a textile design. The schematic diagram is derived from analysis carried out on the basis of tacit knowledge and the depth of experience as a printmaker practitioner, general knowledge regarding the design process, pre-thesis designs and information from the literature studies (see sections 2.2, 3.3 and 3.3.1).

The design variables in level 1 are divided into 'geographical location and position of artefact' and 'other design variables' (see level 1, Figure 7.3). The former refers to how and where on Earth the intended textile is placed. This includes aspects such as where the textile is positioned (i.e., latitude and longitude), the angles adopted by the textile relative to the horizontal and vertical, as well as whether in an indoor or outdoor location. If the product were a non-site-specific textile, it is likely that the printmaker practitioner will not be the one to decide these variables, making it more difficult for the printmaker practitioner to consider their effect on the aesthetic outcome. For example, the textile might be mounted in a location with high UV-radiation for long periods. This

might lead to an undesirable, long-term effect on the aesthetic colour outcome, if UV-resistant dyes/pigments have not been used. To a certain extent, the impact of these particular design variables in this type of design application will be based on chance rather than the control of the print design maker in defining the aesthetic expression. However, it is reasonable to assume that these factors will only have a minor impact on the end result. The variable ‘geographical location and position of artefact’ is, therefore, categorised as a ‘partly controllable design (see cyan text, level 1, Figure 7.3).

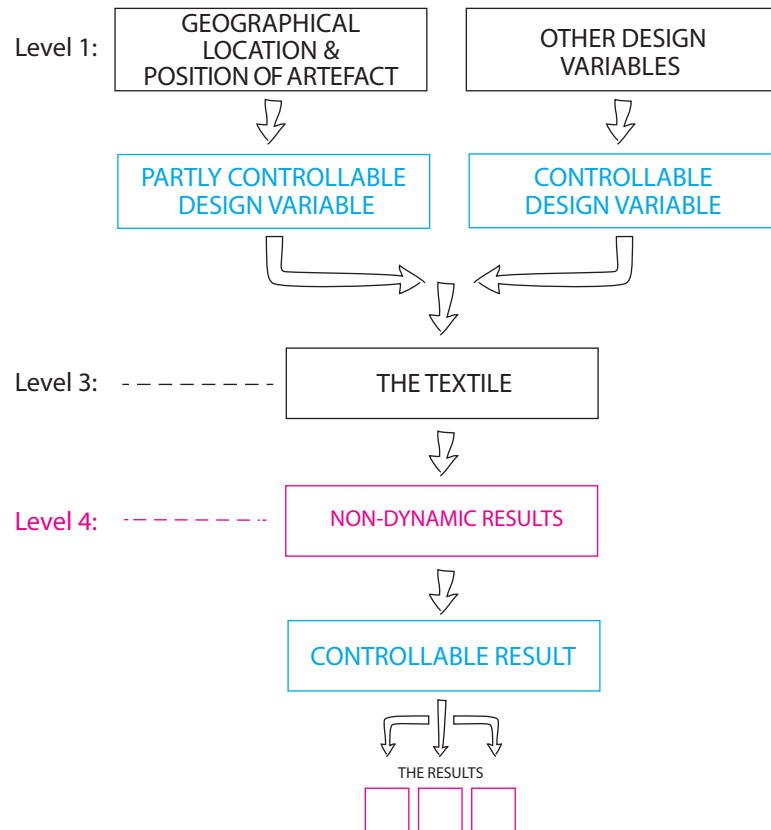


Figure 7.3 Schematic diagram I, non-back-illuminated textiles printed with ‘traditional’ pigments and/or dyes.

The term ‘other design variables’ in level 1, Figure 7.3, refers to all other design variables that the printmaker practitioner could consider in relation to the intended aesthetic outcome. This can include the non-dynamic dyes and/or pigments, textile materials, printmaker related technologies that will be used, or the final textile application (such as bedding, tablecloths, cloth fabric). In a specific design application, certain limitations might inevitably affect decisions that will be likely to have an impact on the aesthetic outcome. For example, this could involve production limitations, which might require a certain technical pre-setting that the printmaker practitioner must accommodate. Within this thesis, however, specific circumstances, such as those

involving this limitation, are established as factors that the print design maker in the broader sense can control. ‘Other design variables’ are, therefore, categorised as ‘controllable design variable’ (see cyan text, level 1, Figure 7.3).

In the case of the applications illustrated in diagram I, the ‘space/surfaces’ that the design will include is the actual textile (see level 3, Figure 7.3). Also, since there is no activation scenario, level 2 has been excluded to simplify comparison with the other diagrams. This textile will only provide non-dynamic results, because the textile neither is back-illuminated nor uses any dynamic materials (see level 4, Figure 7.3) and will thus more or less provide a set static expression. The static aspect of the design provides the printmaker practitioner with significant control over defining the aesthetic expression. The printmaker practitioner’s aesthetic design and production-related choices as well as the partly controllable context, in terms of location and placement of the textile, will determine how the viewer will perceive the textile.

The second type of design applications, presented in schematic diagram II, Figure 7.4, involves ‘smart’ textile print applications using a ‘traditional’ heating solution to activate thermochromic dyes’. A ‘traditional’ heating solution refers to the heaters that have been commonly used as activators for thermochromic dyes prior to the research described in this thesis, e.g., electrical heating mechanisms powered by batteries or mains electricity, body heat, warm air or hot liquids. For examples of these types of solutions, see sections 2.1.4 and 2.1.5. In addition, diagram II, includes some applications when a photovoltaic is used as an energy supply, such as when the harvested energy is stored within a battery and used during the night when the textile is no longer back-illuminated, or when the photovoltaic is separate from the textile (for example, if the textile is indoors, non-back-illuminated, and the photovoltaic is placed in sunlight outdoors), as introduced in chapter 6. Diagram II, Figure 7.4, represents the investigated parameters ‘non-back-illuminated textile’ and ‘dynamic’ describing the type of design applications that have been printed with dynamic materials, but that are not back-illuminated.

Over the past number of years, there have been a number of examples of applications involving these aspects in smart textile research, for example interactive textiles such as wall hangings, responsive rugs or garments. (Mayer, 2002; Berzina, 2004; Orth, 2004; Berzowska and Broley, 2007; Ledendal, 2009; Persson, 2009; Worbin, 2010; Watson, 2011) The analysis leading to schematic diagram II is based on the research carried out within the author’s MA thesis and other publications (see section 2.1.4-2.1.5).

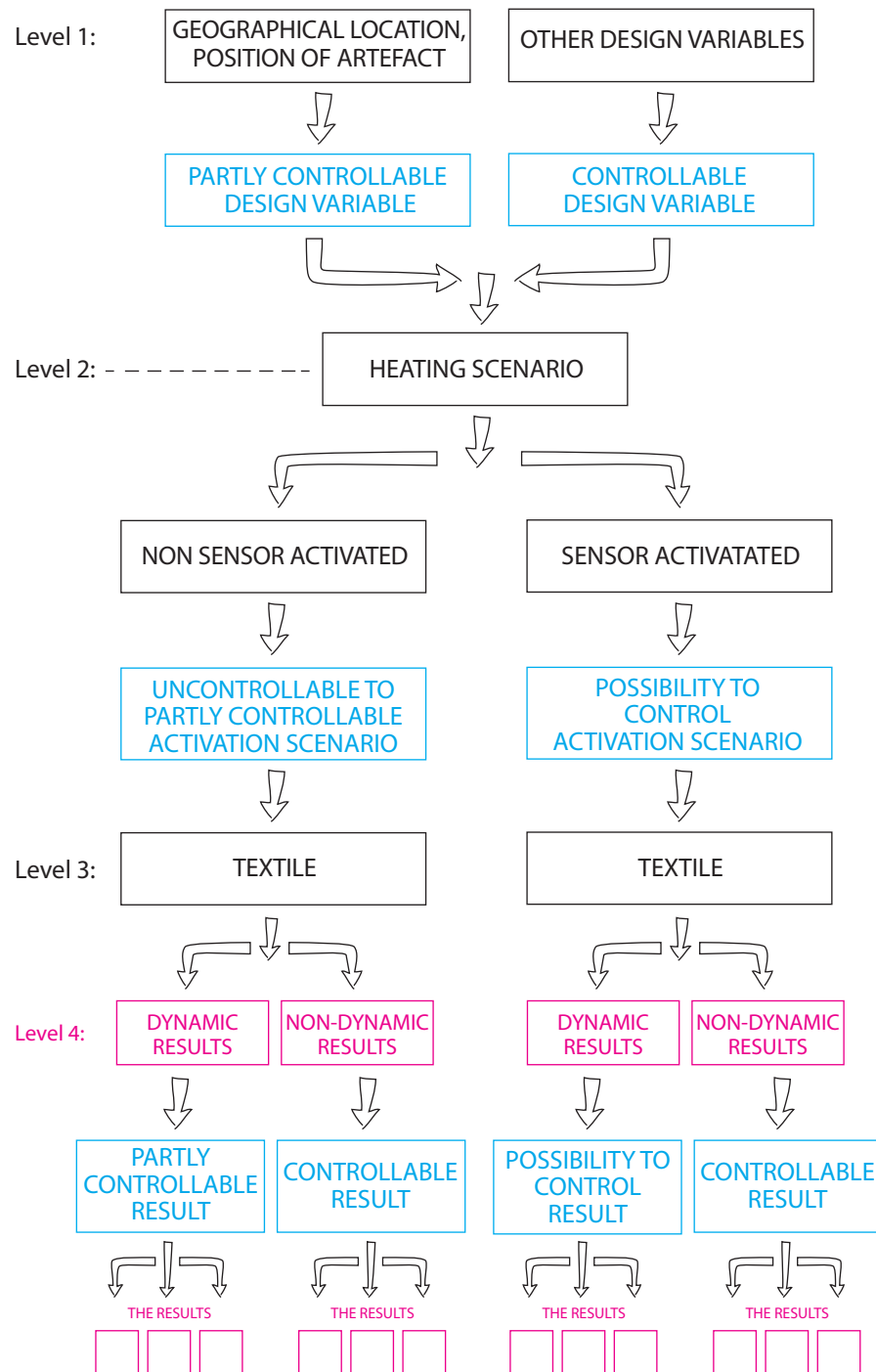


Figure 7.4 Schematic diagram II, a non-back-illuminated textile printed with dynamic dyes.

As in diagram I, the partly controllable variables refer to the placement of the textile, and the controllable variables including the design and production related choices influenced by decisions of the printmaker practitioner (see level 1, Figure 7.4). As discussed in sections 2.1.5 and 6.2.3, the design decisions related to the activation scenario for the intended application of diagram II can lead to heating solutions with different levels of controllability. As discussed in section 4.5.3, sensor-activated heaters

can affect the design variable ‘time interval/temporal pattern’, either in a random or controlled way or a combination of both. The outcome is defined through design decisions made by the printmaker practitioner in terms of whether the heating system is created to act either in a controlled or a more random manner. In contrast, non-sensor activated heaters, for example body heat, sunlight, warm air and hot liquids, as described in section 2.1.5, will provide a more uncontrolled and random activation, as discussed in section 4.5.3. Therefore, the activation scenario provides two possible outcomes as illustrated in schematic diagram II (see level 3, Figure 7.4). A more controlled means of activation will consequently provide a greater level of control in defining the dynamic aesthetic result, compared to a system of activation based more on chance (see level 4, Figure 7.4). The non-dynamic result will provide the same level of control over the aesthetic outcome of the textile applications as those described in diagram I.

7.1.2 *The back-illuminated textiles*

This section explains schematic diagrams III and IV, which represent textile applications that are back-illuminated. Schematic diagram IV also includes colour-changing dynamic materials, e.g., thermochromic dyes.

Schematic diagram III outlines the level of complexity for textile design applications that include a back-illuminated textile printed with non-dynamic dyes (see Figure 7.5). This could encompass applications such as curtains or sun-screening textiles, printed with the ‘traditional’ dyes/pigments. The development of schematic diagram III is based on the research conducted leading to this thesis.

The partly controllable variables in level 1 refer to the placement of the textile, as in diagrams I and II (see level 1, Figure 7.5). As before, these controllable variables refer to the design and production related choices and decisions of the printmaker practitioner (see level 1, Figure 7.5). Level 2 is excluded from diagram III, as in diagram I, due to the absence of activation scenarios. The differences between diagrams III, compared to I and II, are the addition of a *third category* in level 1 of diagram III; ‘weather & time/day/year’ (see level 1, Figure 7.5). This category is defined as ‘an uncontrollable design variable’ because weather and sunlight conditions are obviously outwith the control of the printmaker practitioner. Instead, the designer requires to understand the effects of the weather variables in order to create a design solution that reacts as far as possible in accordance with the weather, as discussed in

chapter 5. The presence of sunlight, additionally, results in three different possible levels of the ‘extended imagery’: *the textile*, *the intermediate zone* and *the incident surfaces*, as defined in section 5.8 (see level 3, Figure 7.5). This feature sets the back-illuminated applications apart from the two types of non-back-illuminated applications previously discussed. Each of the areas within level 3 of these types of application is divided into ‘dynamic’ and ‘non-dynamic’ results (see level 4, Figure 7.5). The ‘intermediate zone’ and the ‘incident surfaces’ provide a ‘dynamic result’, whereas the textiles printed with non-dynamic dyes/pigments result in a ‘non-dynamic result’, a static colour outcome. In this case, a minor change in the colour outcome within the textile might be observed when the illumination changes because colour perception depends on the illumination conditions. (Parraman and Rizzi, 2008, p.1)

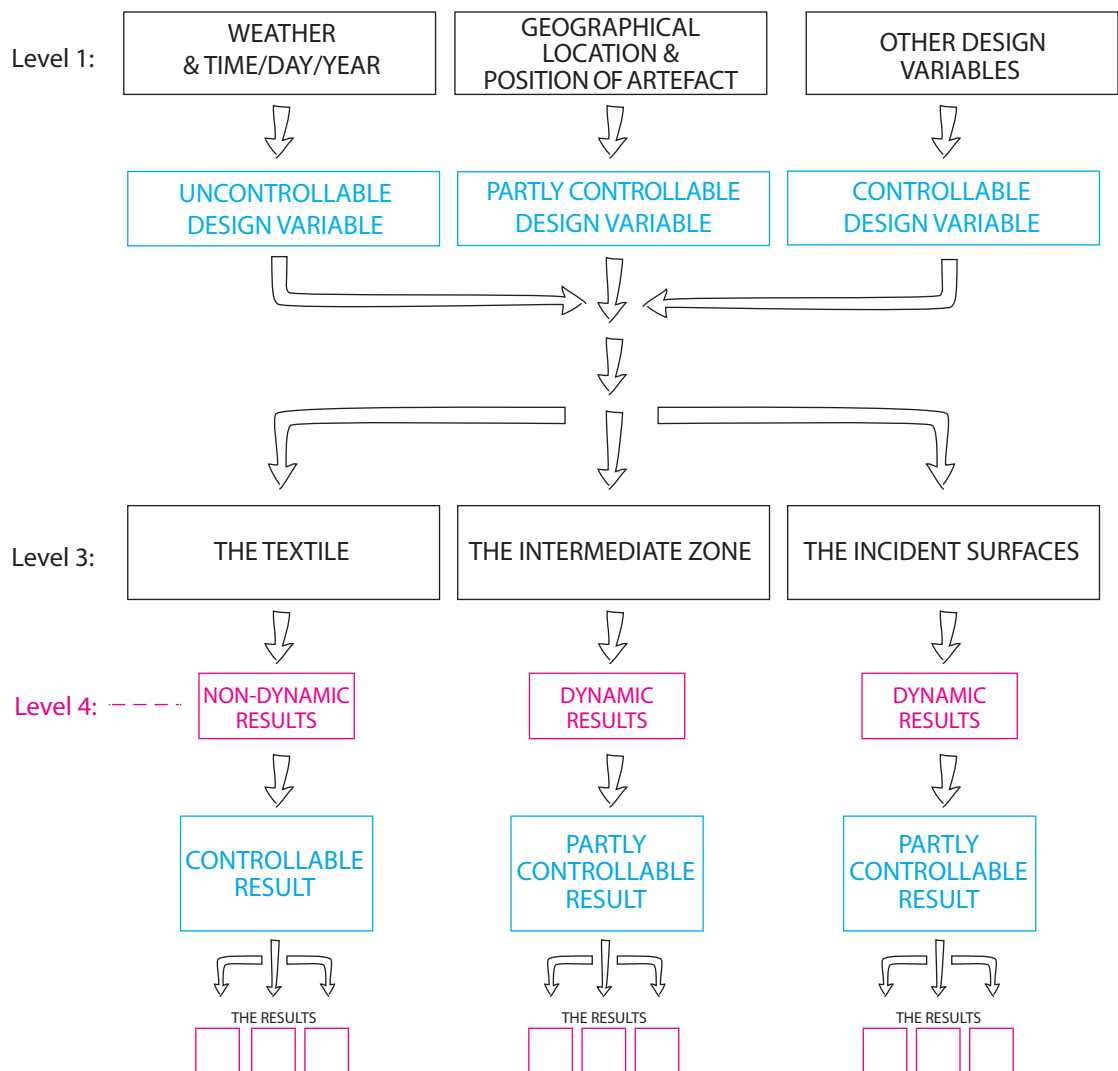


Figure 7.5 Schematic diagram III, back-illuminated textiles printed with ‘traditional’ pigments and/or dyes.

Schematic diagram IV encompasses textiles that are back-illuminated and printed with dynamic dyes. This diagram is also derived from the research described within this thesis (see Figure 7.6). Examples of applications relevant to such textiles include heat responsive sunscreens or window covering textiles.

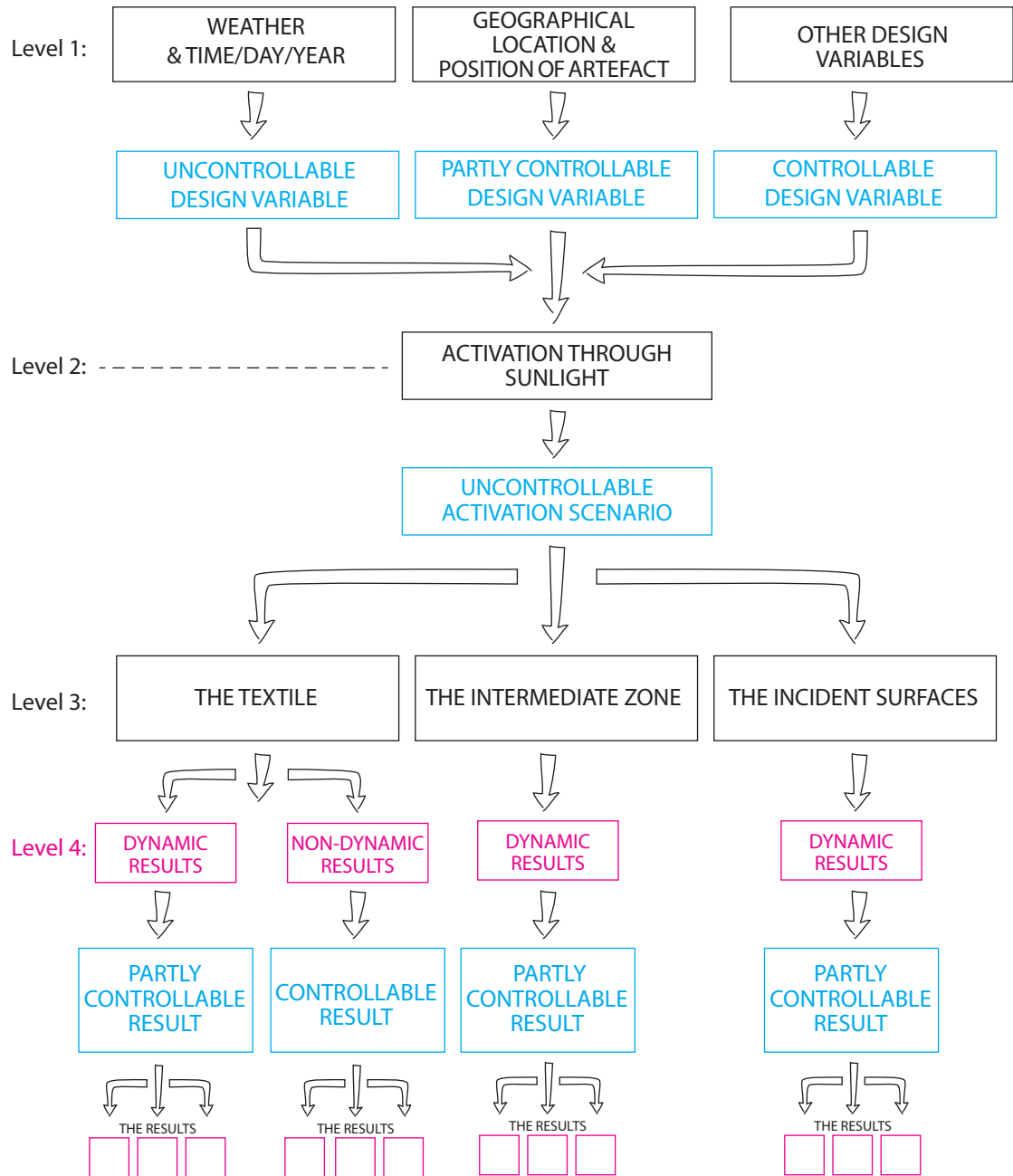


Figure 7.6 Schematic diagram IV, back-illuminated textiles, printed with dynamic dyes, where parts of the design might also use ‘traditional’ pigments and/or dyes.

Levels 1 and 3 in schematic diagram IV are identical with those levels in schematic diagram III (see Figures 7.4 and 7.6). However, diagram IV, additionally has a level 2, due to the activation scenario of the printed thermochromic dyes by solar

activation, either directly, as discussed in chapter 4, or indirectly in situations where the photovoltaic is incorporated into a back-illuminated textile, as discussed in chapter 6. Each of the areas within level 3 in diagram IV is, as in diagram III, divided into ‘dynamic’ and ‘non-dynamic’ results (see level 4, Figure 7.6). ‘The intermediate zone’ as well as ‘the incident surfaces’ contain dynamic levels, as within diagram III. However, the level involving the physical textile provides the possibility of both a ‘dynamic’ and a ‘non-dynamic’ result, depending on the relative proportions of thermochromic and ‘traditional’ dyes/pigments used. In conclusion, it is the design process that is most challenging for the printmaker practitioner to produce a controlled design result. However, as demonstrated throughout this work, which resulted in the guidelines developed as described in chapters 4 to 6, it is possible to control the outcome to a certain extent.

7.1.3 *Suggested guidelines to increase control of the aesthetic outcome*

This section presents how the findings from the research described in chapters 4 to 6 can be used to extend the control of the aesthetic outcome of textile applications, in relation to schematic diagrams II, III and IV.

The previous sections have defined the four schematic diagrams in relation to designers’ ability to exercise control over a defined aesthetic outcome. The definition refers to the designer’s ability to oversee the control of how the viewer will perceive parameters of the textile expression, such as shape, colour, motif, material etc. As defined in previous sections, the discussion of the definition has disregarded the subjective aesthetic qualities, such as whether or not one likes the design. Of course, a controlled outcome may not always be what designers are intending to achieve. Interesting design results may be achieved by using chance to a large extent when defining the aesthetic outcome. However, the decision to use randomness remains an active choice, over which the designer needs to have control. Understanding the process of creating a set-up built on chance is equally important, compared with a set-up built on control. The processes involved in working with colour changing designs can be understood by reflecting upon in which of the levels in the schematic diagrams the less controllable factors are located. Examples of such changing designs are in the design applications represented in diagrams II and IV, and in the effects of utilizing the sunlight as in the design applications represented in diagrams III and IV.

The designer has to consider which of these less controllable factors he/she can influence. For example, the variable of location and geographical position may be set for a site-specific design. If such a site-specific design is required, then there is information that requires to be taken into consideration. Such information might be curves of the ambient temperature with time when activating thermochromic dyes, time of sunrise and sunset, as well as the level of incident illumination when creating projected light and shadow imageries. Though weather changes will not be a factor over which the designer can exercise control, they can be useful features to use to create an expression built more on chance.

The final factor that provides a low level of controllability, as illustrated within the schematic diagrams, are the set-ups of the activation scenarios for thermochromic dyes. When the set-up for activating the thermochromic colour change is constructed around a sensor-controlled system, the change can be programmed in detail. However, when it is based on sunlight, human touch, or other non-sensor activated systems, it will be based more on chance. Within the design process the designer can reflect upon the final design outcomes by relating the choice of activation scenario of the thermochromic dyes to the design variables defined in this thesis as ‘amount of thermal energy’, ‘heating ability’, ‘time interval/temporal pattern’ and ‘distribution of heat’ (see sections 4.5.1-4.5.4 and 6.2.1-6.2.4). The designer will acquire information regarding the activation for the intended expression/product by ‘setting’ and ‘answering’ questions that arise during the analysis of the expression of the intended colour change, as defined in section 4.6. The analysis results in a ‘framework’ of requirements for the activator with the aim to achieve the intended aesthetic expression of the colour change. The decision regarding the selection of activation scenario would lead the designer to the most applicable of the three diagrams; either one of the two versions of diagram II (sensor or non-sensor controlled) or diagram IV. Depending on the preferred level of control versus randomness, this would provide further information towards choice of the appropriate activator.

A choice of activation scenario that provide a low level of controllability does not necessarily have to result in no control over the aesthetic outcome. Designers can increase control over the outcome by understanding the impact that an activator has on the dynamic nature of the thermochromic dyes. This may be provided through analysing the set of individual design variables for the specific activation scenario, and

thus understanding what the designer can influence but also what he/she cannot influence. For example, the variables for the activation scenario in direct sunlight, ‘amount of sunlight’, ‘time interval’, ‘temporal pattern’, ‘contact surfaces’, ‘ambient temperature’ and ‘distribution of sunlight’ will provide information as to how direct solar energy relates to thermochromic leuco dyes (see sections 4.4.1-4.4.6, as well as 4.7). For example, the nature of sunlight would provide a defined colour change within the imagery all-over the textile substrate (due to the ‘distribution of sunlight’) during the hours of daylight, but that might reverse any time during daylight depending on the weather conditions (due to the ‘time interval’ and the ‘temporal pattern’). Through understanding these parameters, designers can create a defined aesthetic outcome with a ‘controlled randomness’. The decision on the choice of dye activation temperature might be more difficult without knowledge of where the textile will be used. This is due to the effects that the environment and the set-up of the textile application have on the temperature rise within the fabric material, as studied within the work described in chapter 4. The temperature of the sun-projected textile relates to a combination of effects of the design variables ‘amount of sunlight’, ‘contact surfaces’, ‘ambient temperature’ and ‘distribution of sunlight’. It should be possible to develop hypotheses regarding the choice of dye activation temperature if the designer can assess relevant background information about the application, in order to provide an approximate range of ambient temperatures. This could for example, be whether the textile will be aimed at indoor or outdoor use, or if the product is intended for winter or summer time. This information may be assessed in the design of a product, especially if the designer knows the market (geographical) that the product is intended for. However, using activation by direct sunlight for more general products (i.e., that are not site-specific) will add the factor of randomness to how the printed dye will activate and deactivate, contrasting with using a system-controlled activation scenario.

Another factor that might make the printmaker feel that he/she is not in control in defining the aesthetic outcome of the sunlight-activated textile printed with thermochromic dyes may be the difficulty in visualising the result of the colour change during the design process, without testing the designs on full-scale, and with several different temperature intervals. A test print of an intended design can provide the designer with increased understanding of the behaviour of the colour change, seen from the perspective of the aesthetics, in both colour states 1 and 2, but also during the

transitional phase. The lighting and heating scenario using a photography studio as described in section 3.8 provides an example of how the designer could investigate the potential design outcome on a small scale. This facility provides the possibility to investigate how the imagery design would change colour when different temperature levels are reached, as well as how the variety in angles of incident sunlight would affect the expression. If the application was not site-specific, the printmaker might not be able to determine the exact aesthetic outcomes of the intended design, but would gain a greater understanding of several possible design outcomes. This type of analysis of the dynamics of the aesthetic expression of the design would be facilitated by filming the results, for example as illustrated in Films 1-7 on the CD-ROM that accompanies this thesis.

A factor that is common to both schematic diagrams II and IV, the two situations where thermochromic dyes are used, is the lower level of controllability of the colour outcome. Under normal circumstances, the majority of the features of the design variables labelled 'other design variable', such as colour, texture, shape and imagery will be able to be controlled by the designer. One exception in the use of thermochromic dyes is the colours that the design might display during the transitional phase. Even if, at first sight, the definition of the colour outcome from the use of thermochromic dyes compared to permanent pigments appears to be rather more challenging, they will still behave within a framework defined by their chemical structures, i.e., they will alter between colour state 1 and 2 when the activation temperature is reached. By studying the 'mixing principles of thermochromic dyes', as presented in section 4.4.1 and Figures 4.4-4.5, the colour limitations of these dyes may be understood. The complexity of the design can be increased by using combinations of thermochromic dyes with different activation temperatures (see Figures 4.6-4.7). However, the author strongly recommends that designers work hands-on by testing samples printed onto substrates so that the actual colour outcome of the imagery can be studied during all the colour states, to complement considerations based on colour changing design in theory.

The process of utilizing sunlight to create a three-dimensional space to work within, as represented in the design applications of schematic diagrams III and IV, can be further controlled by studying the effect created between the factors of *how* the textile is designed and the presence of sunlight. From the textile design printer's perspective, both back-illuminated applications provide the same possibilities in

controlling the design outcome of ‘the intermediate zone’ and ‘the incident surfaces’. An enhanced understanding of the aesthetic design outcome of these levels can be achieved by studying how the aesthetics change within these levels based on the design of the physical textile, as discussed in section 5.8. As regards the control of these two aspects of ‘the extended imagery’, the influence of the sunlight provides the possibility to affect the quality of the light (if any) that passes through the textile, as well as the projected light and shadow imagery. Examples of relevant design decisions in this context involve a consideration of light transmittance levels (%T) of the textile, which are influenced by the selection of substrate materials and appropriate fabric treatments, as discussed in sections 5.3-5.5. In order to increase the control over the aesthetic outcome of the projected light and shadow imagery, this thesis identifies the following key variables, which require to be studied; ‘the movement of the position of the projected imagery’, ‘the movement within the imagery’ and ‘the movement within the composition’ (defined in section 5.6.2).

To further understand the effects on a specific design outcome when using sunlight as an uncontrollable factor within the design process, the key variables identified above can be studied using set-ups D and E (see section 3.7.4). The daylight laboratory (set-up E) was found to be very useful when investigating an intended textile imagery design. The use of such a laboratory is therefore recommended as a fruitful means to visualise an intended end result within the ‘the intermediate zone’ and ‘the incident surfaces’ in the design process of schematic diagrams III and IV, while recognising that this provides only a simulation of the real situation using a scaled model. It was found to be beneficial to make both video and photographic records of the working processes involved in the investigations conducted in the daylight laboratory. The large quantity of information thus documented allowed a more detailed analysis at a later date, compared with what was possible during the short time in the daylight laboratory. A team of three conducted the work in the daylight laboratory; one focussed on the documentation and recording while the other two operated the artificial sun (one moving the lamp simulating the sun, and the other moving the metal arc that holds the lamp in position). This was found to be the optimum way of working, at least for this particular daylight laboratory. The research within this thesis has shown that the understanding and validation of the aesthetic outcome can be enhanced when a design is carried out for a site-specific application, for example the sun-sail designs for the street in Seville, (section 5.6.2). The

use of such an application allows the printmaker practitioner to investigate the uncontrollable factors relating to the placement of the textile and the position and quality of sunlight in schematic diagrams III and IV, for example, as illustrated in the investigation described in sections 5.6.3 and 5.7.

7.2 Will these research outcomes impact on sustainability?

This section discusses the potential advantages in terms of sustainability that the work within this thesis has provided. The thesis has a focus on using sunlight to activate thermochromic dyes within textile applications. The main motivation for this research was that the author was critical towards the environmentally unsustainable ways that have traditionally been used to activate thermochromic dyes in a majority of applications. Prior to this thesis, the main ways of heating thermochromic dyes in textile design applications have involved the use of a variety of electrical heating mechanisms, see section 2.1.4. In contrast, in this thesis, the sole activator used has been sunlight, either directly or indirectly by the use of photovoltaic cells. The alternative approach based on direct solar activation has provided a solution for design applications (chapter 4) that does not need additional components to activate the dyes, such as heaters, wires, etc. Not only does this provide a more straightforward production process, with less material usage, it also provides an end product that will be easier to recycle, because of the reduced number of material components (Fletcher, 2008). For an application where direct sunlight is not an option, this thesis has presented a proof of concept for an alternative solution where the energy input is contained within the design application provided by a renewable energy source (chapter 6), in contrast to previous solutions, which relied on batteries or mains electricity. The global usage of solar energy remains small compared to other energy sources. In 2012 solar energy only accounted for 0.5% of the global electricity supply. (Wilson, 2013) However, there is immense potential for growth in its use as a renewable energy source, since the sun is a powerful, plentiful and non-diminishing resource. (Smith, 2001, p.37)

The use of solar activation, direct or indirect, does not of course make these textile applications completely sustainable. However, it provides a more sustainable system, compared to ‘traditional’ electrical heating solutions. Additionally, the work within this thesis provides the potential to exploit a projected positive future for further developments of photovoltaics integrated into textiles, as discussed in section 6.3 based on the method of future scenarios. The probability of future significant technical

developments in solar energy conversion will open up design possibilities utilising more sustainable energy solutions in applications of textiles printed with thermochromic dyes that use heat circuitry systems powered using harvested solar energy. Fry argues that sustainability is a way of living, a choice we actively have to make regarding how we view the Earth's resources as well as how we consume and use them. He states that it is a collective project worldwide, and that the change cannot happen by itself, but must come from us by, for example, the way we design. (Fry, 2009, pp.43-45) By actively working towards more sustainable design alternatives using renewable energy sources, this thesis makes an important contribution to meeting this statement.

A parallel can be drawn to the way that Fletcher, based on Max-Neef's definition of human needs, discusses how fashion is satisfying our desires both on a material and a non-material level. Fletcher writes that both psychological and emotional needs can be met through consumer flow, but that these needs will only be met momentarily. On the other hand if we, according to Fletcher's use of Max-Neef's theories, can shift the focus towards making artefacts a tool to obtain quality of life, rather than letting the artefact be the reason for and focus of it, Fletcher argues that sustainable consumer goods might in this way be able to enhance both the environment and human well-being. (Fletcher, 2008, pp.120-124) The fact that when the sun shines directly on a textile, as demonstrated in chapter 4, it can activate the thermochromic dyes without negative environmental impact creates the potential for design systems involving thermochromic colour changing textile applications to provide the consumer with such non-material qualities. A similar argument may be made for the indirect activation system, based on solar energy harvested with photovoltaics for which the potential for indirect solar activation of printed thermochromic dyes has been demonstrated (see section 6.1). In her discussion, Fletcher also underlines the importance of the aesthetics of these products in sustainable and eco-friendly design. Fletcher points out the role of the designer as an initiator when working towards changing the patterns of behaviour in the consumer society, by not only choosing the more sustainable alternative but also communicating this feature through the expression of the product. (Fletcher, 2008, pp.126-134) The solution to this challenge is in the hands of the individual textile designer.

7.3 Possibilities for future research

This section suggests ideas for projects that have the potential to build on the work presented within this thesis.

A continuation of the work described in this thesis is suggested, aimed at assessing how other textile design practitioners apply the guidelines described by the design variables of chapter 4. For example, this research might be carried out through the method of workshops, where practitioners are instructed to use the new design variables within a design assignment. The outcomes of the workshop would be analysed through documentation and in-depth interviews in relation to the current definitions and proposed use of the variables. Suggested modifications to the definitions and use of these design variables would be open for discussion and subsequent evaluation. An additional interesting aspect would be to investigate the usefulness of the new variables as applied to thermochromic liquid crystals, in comparison to the use of leuco dyes.

A suggested continuation of the work of chapter 6 is to construct prototypes that further investigate applications for indirect solar activation through the use of photovoltaics as an energy source. This would aim to establish in detail the design possibilities provided by incorporating photovoltaics into textiles printed with thermochromic dyes and to define future design directions for applications of interest. Further investigation into the development of microheaters on glass wafers providing enhanced efficiency would be of interest, to establish the potential to create an even more energy saving heating system. This future research, based on the outcomes in chapter 6, would be interdisciplinary, incorporating not only designers (from areas such as textiles and architecture) but also engineers and physicists.

From the outcomes in chapter 5, the thesis has also examined the dynamic aesthetic outcomes, related to the light and shadow imageries and light quality, which are provided by surface techniques available to the printmaker practitioner that lead to light translucency. The investigations described in chapter 5 were conducted so that the entire concept involving the effect of the sun on the thermochromic textiles and the formation of extended imagery could be understood. However, the depth of the investigations in these areas was restricted by inevitable time limitations. Establishing deeper understanding of the complexities involved in these areas is suggested as a further important path for future research.

Chapter 8 Reference list

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Appendix A Dye recipe – thermochromic leuco dyes and permanent pigments

A.1 Recipe of base batches of permanent pigments

Pigment Yellow base (30/1000): 30g slurry imperon yellow K-R/1000g pigment binder

Pigment Red base (30/1000): 30g slurry Bricoprint red/1000g pigment binder

Pigment Orange base (30/1000): 30g slurry aquarine fluorescent orange/1000g pigment binder

Pigment Blue base: 30g slurry acramin blue/1000g pigment binder

A.2 Recipes of the pre-set colours, mixed from permanent pigments

Yellow (Y) = Yellow base (30/1000)

Orange (O): 28g yellow base (30/1000), 5g red base (30/1000), 10g orange base (30/1000)

Blue (B1): 2,5g blue base (30/1000), 0,5g red base (30/1000), 7g binder

A.3 Recipe of base batches of thermochromic leuco dye (TLD)

TLD Hallcrest Blue base 31 (10/40): 10g slurry Blue 31°C TLD/40g binder

TLD Hallcrest Blue base 47 (10/40): 10g slurry Blue 47°C TLD/40g binder

TLD Hallcrest Black base 31 (10/40): 10g slurry Black 31°C TLD/40g binder

TLD Hallcrest Black base 47 (10/40): 10g slurry Black 47°C TLD/40g binder

TLD Hallcrest Red base 31 (10/40): 10g slurry Red 31°C TLD/40g binder

TLD Hallcrest Red base 47 (10/40): 10g slurry Red 47°C TLD/40g binder

TLD Hallcrest Magenta base 31 (10/40): 10g slurry Magenta 31°C TLD/40g binder

TLD Hallcrest Magenta base 47 (10/40): 10g slurry Magenta 47°C TLD/40g binder

TLD Hallcrest Magenta base 31 (30/100): 30g slurry Magenta 31°C TLD/100g binder

TLD Hallcrest Magenta base 47 (30/100): 30g slurry Magenta 47°C TLD/100g binder

TLD Hallcrest Magenta/Black base 31: 5gr TLD Hallcrest Magenta 31°C; 0.14gr TLD Hallcrest Black 31°C; 30gr binder

TLD Hallcrest Magenta/Black base 47: 2gr TLD Hallcrest Magenta 47°C; 0.14gr TLD Hallcrest Black 47°C; 40gr Binder

TLD Hallcrest Orange base 22 (10/40): 10g slurry Orange 22°C TLD/40g binder

TLD Hallcrest Yellow base 20 (10/40): 10g slurry Yellow 20°C TLD/40g binder

TLD Matsui Brilliant green base 27 (10/40): 10gr slurry Brilliant green 27°C TLD/40gr binder

TLD Matsui Yellow base 27 (10/40): 10gr slurry Yellow 27°C Th.ch/40gr binder

TLD Matsui Magenta base 27 (30/100): 30gr slurry Magenta 27°C Th.ch/100gr binder

A.4 Recipes of the pre-set colours, mixed from thermochromic dyes some combined with permanent pigments

Magenta (M) 1 (M:100): 10gr slurry TLD Matsui Magenta 27°C/40gr binder

Magenta (M) 2 (M:100): 9gr slurry TLD Hallcrest Magenta/Black base 31; 0.04gr slurry Orange

Magenta (M) 3 (M:100): 9gr slurry TLD Hallcrest Magenta/Black base 47; 0.04gr slurry Orange

Light purple (LP) 1 (C: 50 M:100): 1gr slurry Blue, 9gr slurry TLD Matsui Magenta 27 base (30/100)

Light purple (LP) 2 (C: 50 M:100): 0.4g slurry Blue; 9gr slurry TLD Hallcrest Magenta/Black base 31; 0.04gr slurry TLD Hallcrest Black 31°C (without binder)

Light purple (LP) 3 (C: 50 M:100): 0.8gr slurry Blue; 18gr slurry TLD Hallcrest Magenta/Black base 47; 0.02gr slurry TLD Hallcrest Black 47 °C (without binder)

Dark purple (DP) 1 (Y:20 C:70 M:100): 2,5gr slurry Blue; 8,5gr slurry Magenta 27 base (30/100)

Dark purple (DP) 2 (Y:20 C: 70 M:100): 1g slurry Blue, 9g slurry TLD Hallcrest Magenta/Black base 31; 0.04gr slurry TLD Hallcrest Black 31°C (without binder)

Dark purple (DP) 3 (Y:20 C: 70 M:100): 1.1gr slurry Blue; 9gr slurry TLD Hallcrest Magenta/Black base 47; 0.02gr slurry TLD Hallcrest Black 47 °C (without binder)

Mint-green (MG) (Y:60 C:70): 20g slurry TLD Hallcrest Yellow base 20 (10/40), 8g slurry TLD Matsui Brilliant green 27 base (10/40), 3g slurry Blue

Blue-green (BG) (Y:50 C:100): 7g slurry TLD Hallcrest Yellow base 20 (10/40), 8g slurry TLD Matsui Brilliant green 27 base (10/40), 3g slurry Blue

Appendix B Dye recipe – acid devoré paste

Total: 1000ml

650ml Water (A)

60g Solvitose MVS

5g Wetting agent

150g Aluminium sulphate

135ml Water (B)

Mixing instructions:

In a 1 litre jug and using the electric mixer, very slowly sprinkle the Solvitose MVS into Water (A), Mix thoroughly then run a clean knife around the edges of the jug to incorporate unmixed paste. To this mixture add Wetting Agent. Again mix well. In a separate jug, measure Water (B), add the Aluminium Sulphate and stir well to dissolve, then add to the Solvitose mixture making sure that all the Aluminium Sulphate in the jug has been removed. Mix well with mixer. Decant this mixture into the lidded blue Devoré jug. Prevent wastage by labelling and marking the jug with the date that the paste was mixed.

Appendix C List of material

Table C.1 Materials for the investigation of the substrate materials

Test #	Material	Pigments, dyes, etc.
1.	Woven polyester	Permanente pigment, metallic pigment
2.	Lightweight silk	Opaque pigment, metallic pigment
3.	Cotton cheesecloth	Permanente pigment
4.	Cotton muslin	Permanente pigment
5.	Chiffon (light blue)	Permanente pigment
6.	Silk/nylon stocking	Permanente pigment, metallic pigment
7.	Woven polyester	Disperse dye
8.	Lightweight silk	Cellulose reactive dye
9.	Poly cotton	Devoré print
10.	Polyester-viscose chiffon	Devoré print
11.	Silk-viscose satin	Devoré print
12.	Woven polyester	Transfer print
13.	Tight weave print mesh	Some non-defined, back paint/dye
14.	Tight weave print mesh	Thermochromic leuco dye
15.	Tight weave print mesh	Thermochromic leuco dye
16.	Nylon transfer weave	Thermochromic leuco dye
17.	Non-woven, polyester	Inkjet, photochromic dye, embroidery
18.	Non-woven, polyester	Thermochromic leuco dye, puff print, embroidery
19.	Acetate satin	Thermochromic leuco dye
20.	Acetate satin	Thermochromic leuco dye
21.	Silk-viscose satin	Thermochromic leuco dye
22.	Silk chiffon	Thermochromic leuco dye
23.	Polyester (shiny silvery thin)	Thermochromic leuco dye
24.	Polyester	Thermochromic leuco dye, laser-cut
25.	Silk-viscose velvet	Thermochromic leuco dye
26.	Cotton velvet	Thermochromic leuco dye
27.	Silk-viscose satin	Thermochromic leuco dye, laser-cut
28.	Mohair, plain weave (coloured, striped)	Thermochromic leuco dye
29.	Cotton corduroy	Thermochromic leuco dye
30.	Cotton velvet	Thermochromic leuco dye
31.	Crushed polyester velvet,	Thermochromic leuco dye
32.	Natural fibre wadding,	Thermochromic leuco dye
33.	Polyester nonwoven felt	Thermochromic leuco dye
34.	Polyester fibre wadding	Thermochromic leuco dye
35.	Soft polyester	Thermochromic leuco dye
36.	Velour	Thermochromic leuco dye

Appendix D Statistics of averages temperatures

The temperature curves and the statistics of the average temperatures for the locations used within this thesis: the Scottish Borders, UK, (latitude 55.55°N-55.62°N; longitude 2.89°W-2.84°W), Scania region (Skåne), Sweden (latitude 55.70°N-55.93°N; longitude 13.19 °E-13.55°E) and Seville, Spain (latitude: 37.23°N; longitude: 5.58°W). The statistics for Edinburgh (latitude 55.95°N; longitude 3.22°W) were used for the Scottish Borders and Copenhagen/Kastrup (latitude 55.68°N; longitude 12.57°E) was used for Scania region, taking account of the locations of stations carrying out the measurements. Tables D.1-D.3 present the average temperatures over the period of years from 1961 to 1990 of the respective region.

Table D.1 Edinburgh Airport; Latitude 55.57; Longitude -3.21

Month	Mean Temp °C	Mean Min Temp, °C	Mean Max Temp, °C	Mean Monthly Prec Days	Mean Monthly Days with Thunder	Mean Monthly Sleet/Snow Days
January	3.2 °C	0.3 °C	6.2 °C	n/a	0.0	8.0
February	3.3 °C	0.0 °C	6.5 °C	n/a	0.0	8.0
March	5.1 °C	1.5 °C	8.7 °C	n/a	0.0	6.0
April	7.1 °C	3.1 °C	11.1 °C	n/a	0.0	3.0
May	9.9 °C	5.7 °C	14.2 °C	n/a	1.0	0.0
June	13.0 °C	8.7 °C	17.3 °C	n/a	1.0	0.0
July	14.5 °C	10.3 °C	18.8 °C	n/a	1.0	0.0
August	14.3 °C	10.2 °C	18.5 °C	n/a	1.0	0.0
September	12.3 °C	8.4 °C	16.2 °C	n/a	1.0	0.0
October	9.5 °C	5.9 °C	13.2 °C	n/a	0.0	0.0
November	5.4 °C	2.1 °C	8.7 °C	n/a	0.0	3.0
December	3.9 °C	0.9 °C	6.9 °C	n/a	0.0	5.0

Accessed <http://freemeteo.com/default.asp?pid=24&la=1&md=0&sid=03160&gid=2643743>, 2013-02-28

Table D.2 Copenhagen/Kastrup Airport; Latitude 55.37; Longitude 12.39

Month	Mean Temp °C	Mean Min Temp, °C	Mean Max Temp, °C	Mean Monthly Prec Days	Mean Monthly Days with Thunder	Mean Monthly Sleet/Snow Days
January	.1 °C	-2.0 °C	2.0 °C	n/a	n/a	n/a
February	-.1 °C	-2.3 °C	2.1 °C	n/a	n/a	n/a
March	2.0 °C	-.4 °C	4.8 °C	n/a	n/a	n/a
April	5.6 °C	2.3 °C	9.6 °C	n/a	n/a	n/a
May	10.9 °C	7.0 °C	15.1 °C	n/a	n/a	n/a
June	15.0 °C	11.1 °C	19.4 °C	n/a	n/a	n/a
July	16.4 °C	12.8 °C	20.5 °C	n/a	n/a	n/a
August	16.3 °C	12.5 °C	20.4 °C	n/a	n/a	n/a
September	13.3 °C	10.0 °C	16.8 °C	n/a	n/a	n/a
October	9.6 °C	6.9 °C	12.2 °C	n/a	n/a	n/a
November	5.1 °C	-.2 °C	7.2 °C	n/a	n/a	n/a
December	1.8 °C	.5 °C	3.7 °C	n/a	n/a	n/a

Accessed <http://freemeteo.com/default.asp?pid=24&la=1&sid=06180&gid=2618425>, 2013-02-28

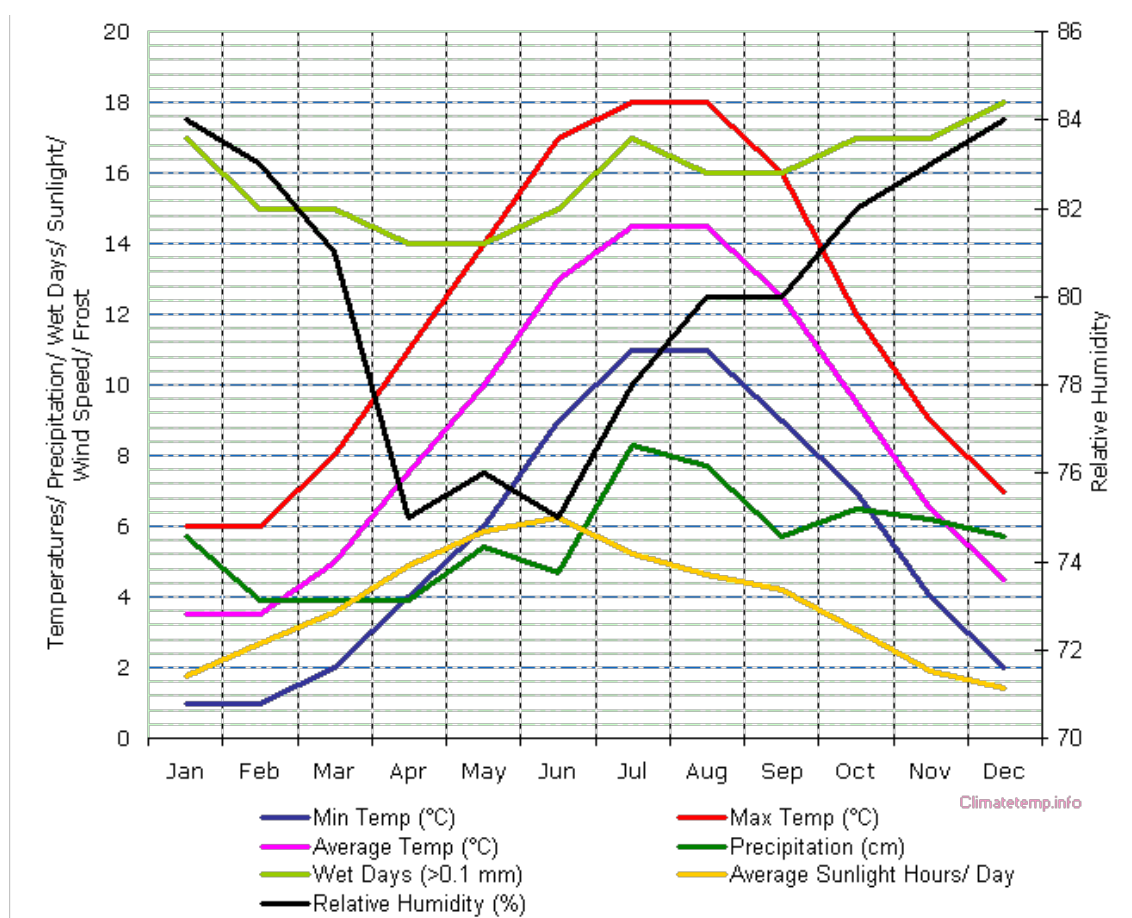
Table D.3 Seville, San Pablo Airport; Latitude 37.39; Longitude -5.98

Month	Mean Temp °C	Mean Min Temp, °C	Mean Max Temp, °C	Mean Monthly Prec Days	Mean Monthly Days with	Mean Monthly Sleet/Snow
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					Thunder	Days
January	10.7 °C	n/a	n/a	7.3	n/a	n/a
February	11.9 °C	n/a	n/a	7.3	n/a	n/a
March	14.0 °C	n/a	n/a	5.8	n/a	n/a
April	16.0 °C	n/a	n/a	6.5	n/a	n/a
May	19.6 °C	n/a	n/a	4.1	n/a	n/a
June	23.4 °C	n/a	n/a	2.1	n/a	n/a
July	26.8 °C	n/a	n/a	0.1	n/a	n/a
August	26.9 °C	n/a	n/a	0.5	n/a	n/a
September	24.4 °C	n/a	n/a	2.1	n/a	n/a
October	19.5 °C	n/a	n/a	5.4	n/a	n/a
November	14.3 °C	n/a	n/a	6.8	n/a	n/a
December	11.1 °C	n/a	n/a	7.4	n/a	n/a

Accessed <http://freemeteo.com/default.asp?pid=24&la=1&sid=08381&gid=3117735>, 2013-02-28

Tables D.4-D.6 and Graphs D.1-D.3 present the average yearly temperatures for the three respective regions.



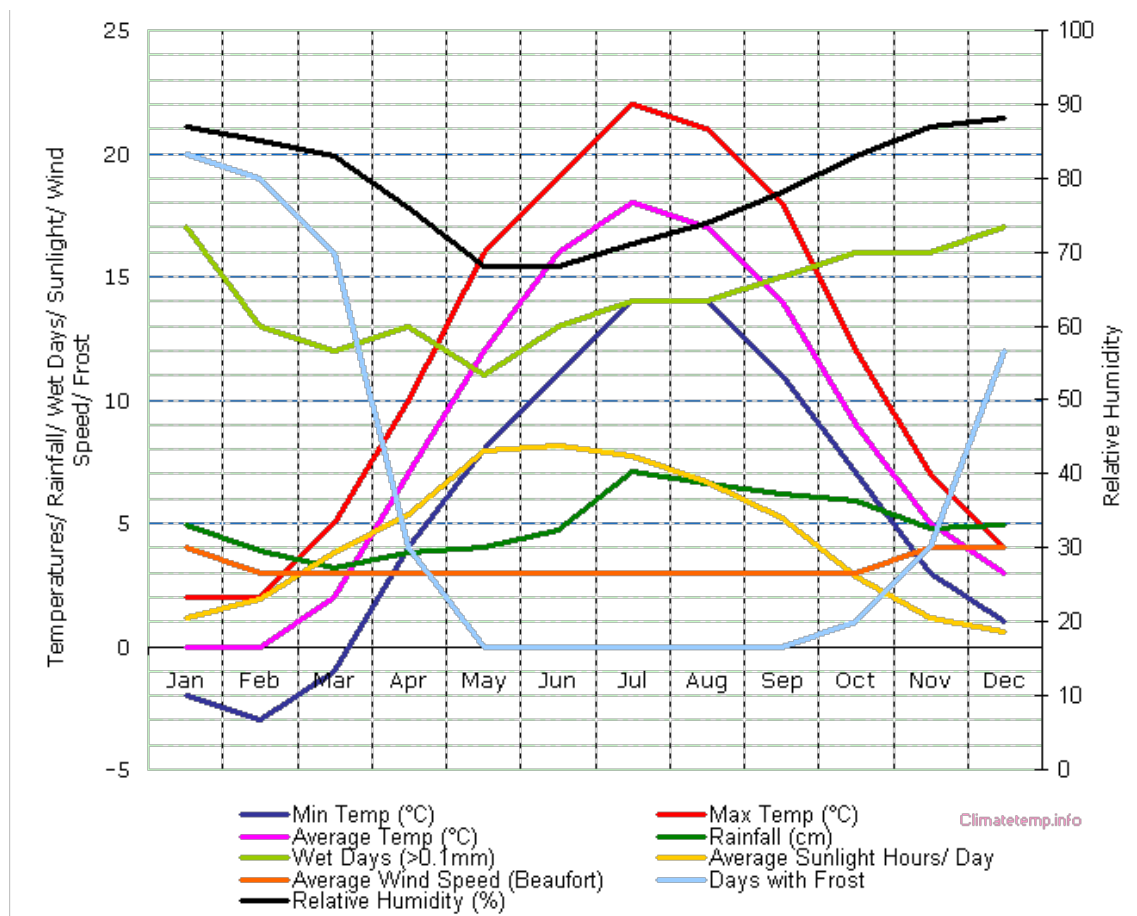
Graph D.1 Climate graph, Edinburgh, UK (altitude 134m)

Table D.4 Average yearly temperatures for Edinburgh, UK

Weather in Edinburgh, Scotland	Average Minimum Temperatures (°C)	Average Maximum Temperature (°C)	Edinburgh Average Temperature (°C)	Average Rainfall/ Precipitation (mm)	Wet Days (>0.1 mm)	Average Sunlight Hours/ Day
January	1	6	3.5	57	17	1.7

February	1	6	3.5	39	15	2.7
March	2	8	5	39	15	3.6
April	4	11	8	39	14	4.9
May	6	14	10	54	14	5.8
June	9	17	13	47	15	6.3
July	11	18	15	83	17	5.2
August	11	18	14.5	77	16	4.6
September	9	16	13	57	16	4.2
October	7	12	10	65	17	3.1
November	4	9	7	62	17	1.9
December	2	7	4.5	57	18	1.4

Accessed <http://www.edinburgh.climatemp.com/>, 2013-02-28



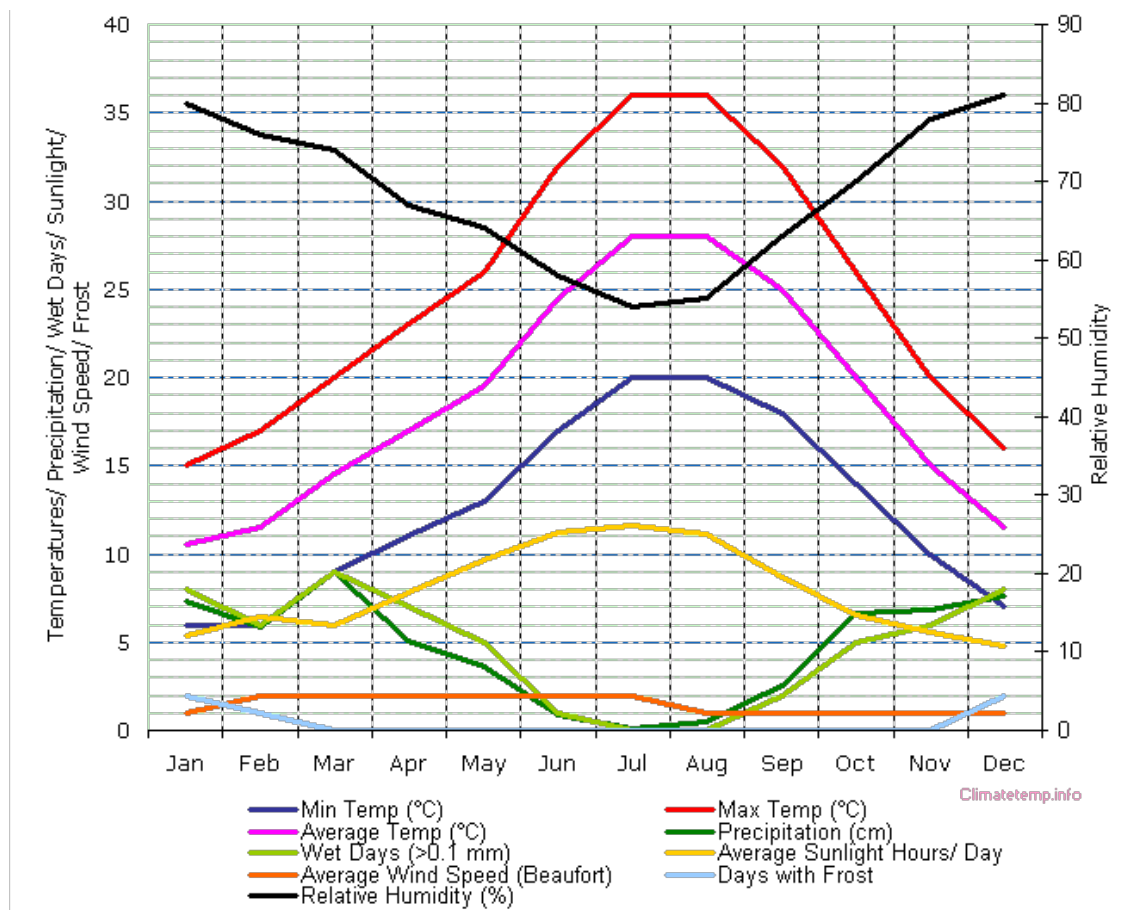
Graph D.2 Climate graph, Copenhagen, Denmark (altitude 9m)

Table D.5 Average yearly temperatures for Copenhagen, Denmark

Weather in Copenhagen, Denmark	Average Minimum Temperatures (°C)	Average Maximum Temperature (°C)	Copenhagen Average Temperature (°C)	Average Rainfall/Precipitation (mm)	Wet Days (>0.1 mm)	Average Sunlight Hours/Day
January	-2	2	0	49	17	1.2
February	-3	2	0	39	13	1.9
March	-1	5	2	32	12	3.8
April	4	10	7	38	13	5.4
May	8	16	12	40	11	7.9
June	11	19	16	47	13	8.2
July	14	22	18	71	14	7.7

August	14	21	17	66	14	6.7
September	11	18	14	62	15	5.2
October	7	12	9	59	16	2.8
November	3	7	5	48	16	1.1
December	1	4	3	49	17	0.6

Accessed <http://www.copenhagen.climatemp.com/#top>, 2013-02-28



Graph D.3 Climate graph, Seville, Spain (altitude 13m)

Table D.6 Average yearly temperatures for, Seville, Spain

Weather in Seville, Spain	Average Minimum Temperatures (°C)	Average Maximum Temperature (°C)	Copenhagen Average Temperature (°C)	Average Rainfall/ Precipitation (mm)	Wet Days (>0.1 mm)	Average Sunlight Hours/ Day
January	6	15	10.5	73	8	5.4
February	6	17	11.5	59	6	6.4
March	9	20	15	90	9	6.0
April	11	23	17	51	7	7.8
May	13	26	20	36	5	9.6
June	17	32	25	9	1	11.2
July	20	36	28	1	0	11.6
August	20	36	28	5	0	11.1
September	18	32	25	25	2	8.7
October	14	26	20	66	5	6.5
November	10	20	15	68	6	5.6
December	7	16	11.5	76	8	4.8

Accessed <http://www.seville.climatemp.com/>, 2013-02-28

Appendix E Supplier list

Acetate films: Colourgen, Elite Essentials HD Screen Film 36'' x 30.5m, EESF-36.

Baker: Laboratory oven and steamer, TFO/S/IM 500mm, 8500W, by Roaches Engineering.

Electronic printing table: Johannes Zimmer, Klagenfurt, Midi MDF 31, 46024, (Austria).

Fabrics (silk-viscose satin, silk-viscose velvet, acetate satin, plain polyester-viscose weave): WBL Whaleys LTD, by Brandford (UK).

Laser machine: FB Series Laser-cutter, by GS UK Ltd. (UK).

Light sensitive emulsion: TC6043 Emulsion Dual Cure, No.14, Thanet Coating Ltd., by Brenntag (UK).

Normal standard pigment binder: Binder SF 20E, white spirit free binder, Bricoprint puff-binder, by Brenntag (UK).

Spectrophotometer: UVNIS Spectrophotometer, Lambda 2, by Perkin Elmer.

Steaming machine: Star steaming.

Thermochromic leuco dye, activation temperatures 25 and 27C, Matsui International Inc. Los Angeles, USA.

Thermochromic leuco dye, activation temperatures 20, 22, 31 and 47, by LCR Hallcrest (UK): Riverside Buildings, Dock Road, Connah's Quay, Flintshire, CH5 4DS, United Kingdom

Puff binder: Bricoprint puff-binder, by Brenntag (UK).

Pigments: Bricoprint, by Brenntag (UK).

Appendix F Ambience'11 - Light and Shadow Play



BARBARA JANSEN, MARIE LEDENDAL

2011

Light and Shadow Play – The sun as an aesthetic trigger for urban textiles

The project investigates how the sun can be utilized to enhance aesthetics through textile surfaces in urban environments. The project explores the interplay of textiles as a sun-screening element within the outdoor public architectural space.

What happens when we use the sun's heat and light to trigger a light and shadow play through a textile surface?

What happens when designing with an unpredictable parameter – the sun – in relation to the predictability of the textile design processes?

The exhibited objects; an interactive 3D model, two animation films and six storyboards, will summarise the research process and results. The interactive model

is open for the audience to interact with via their own observations and explorations.

With this project we put forward the concept of dynamic, energy generating sun sails which incorporate printed solar technology. In this way we can create areas of shadow and generate energy at the same time. We also use thermochromic dye (heat sensitive dye) for a playful colour change in the sails. The sun's changing light will create a dynamic light and shadow interplay. Thus its variation in heat will trigger colour changes. Thereby the aim is to enhance aesthetic experiences within the urban environment.

The emphasis of this project has been to develop design dimensions/solutions to be able to create pattern compositions for a continuously changing pattern. No longer is the designed pattern purely on the textile surface, a second pattern is created. The textile surface and the sun form a constantly moving light- and shadow pattern in the 3D space.



DESIGN CONTEXT

Textiles are widely used as sun shading elements in urban environments, be it in old historical environments, like in the south of Spain, or in modern architecture. (Cf. [1])

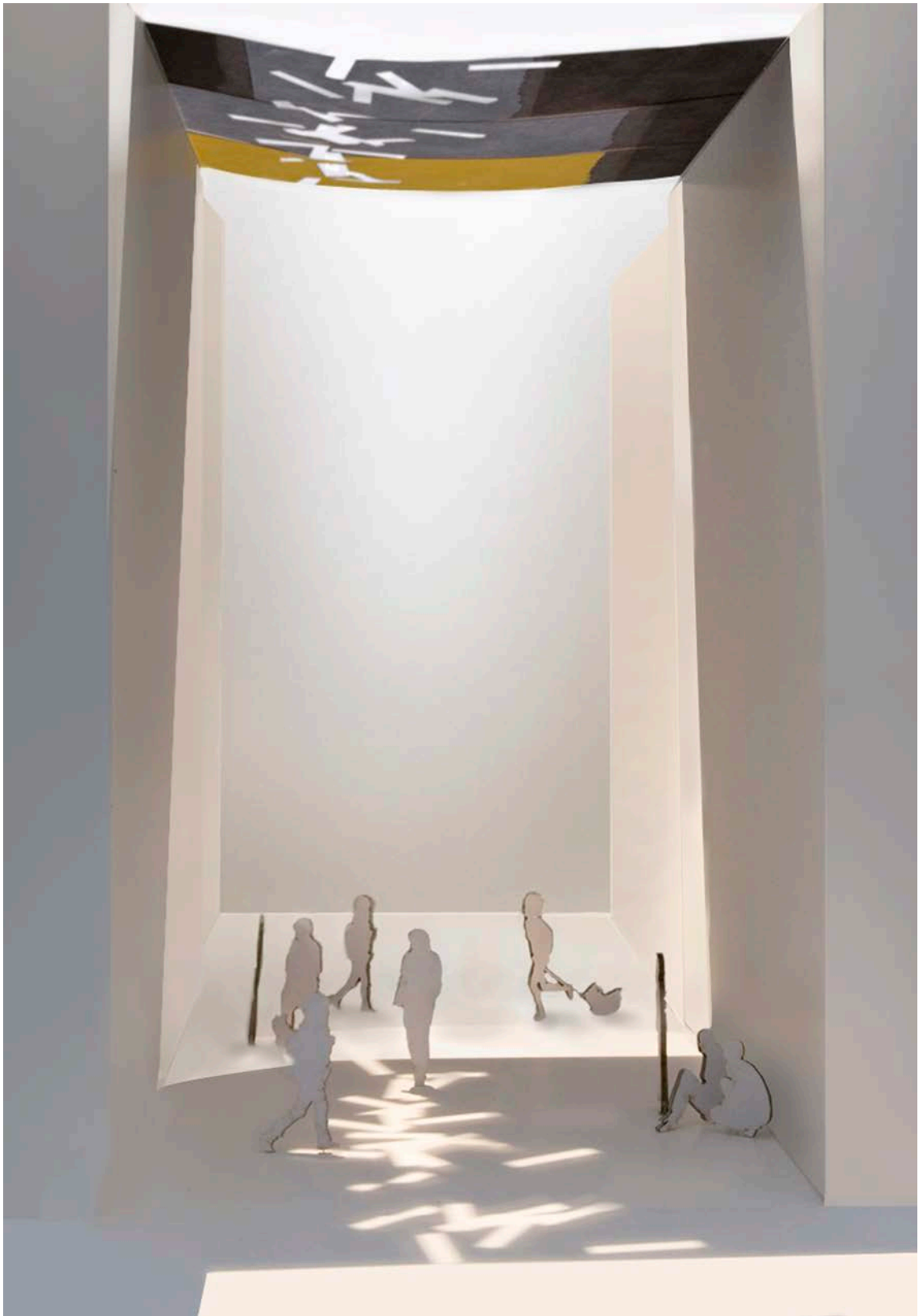
“Why should sunlight always be shut out? [2]” Why not capture both light and heat and make use of it in design. We believe that the integration of solar technology in textile structures offers a great deal of potential for designers in the future. “Increased flexibility and mobility to generate energy are elements which speak for the integration of solar technology into textile surfaces. Developing new surfaces for energy generation through renewable energy sources is an environmentally friendly answer to humanity’s ever-growing energy need. [3]” The current development within solar technology points towards possibilities for printed solar cells onto textile structures. [4]

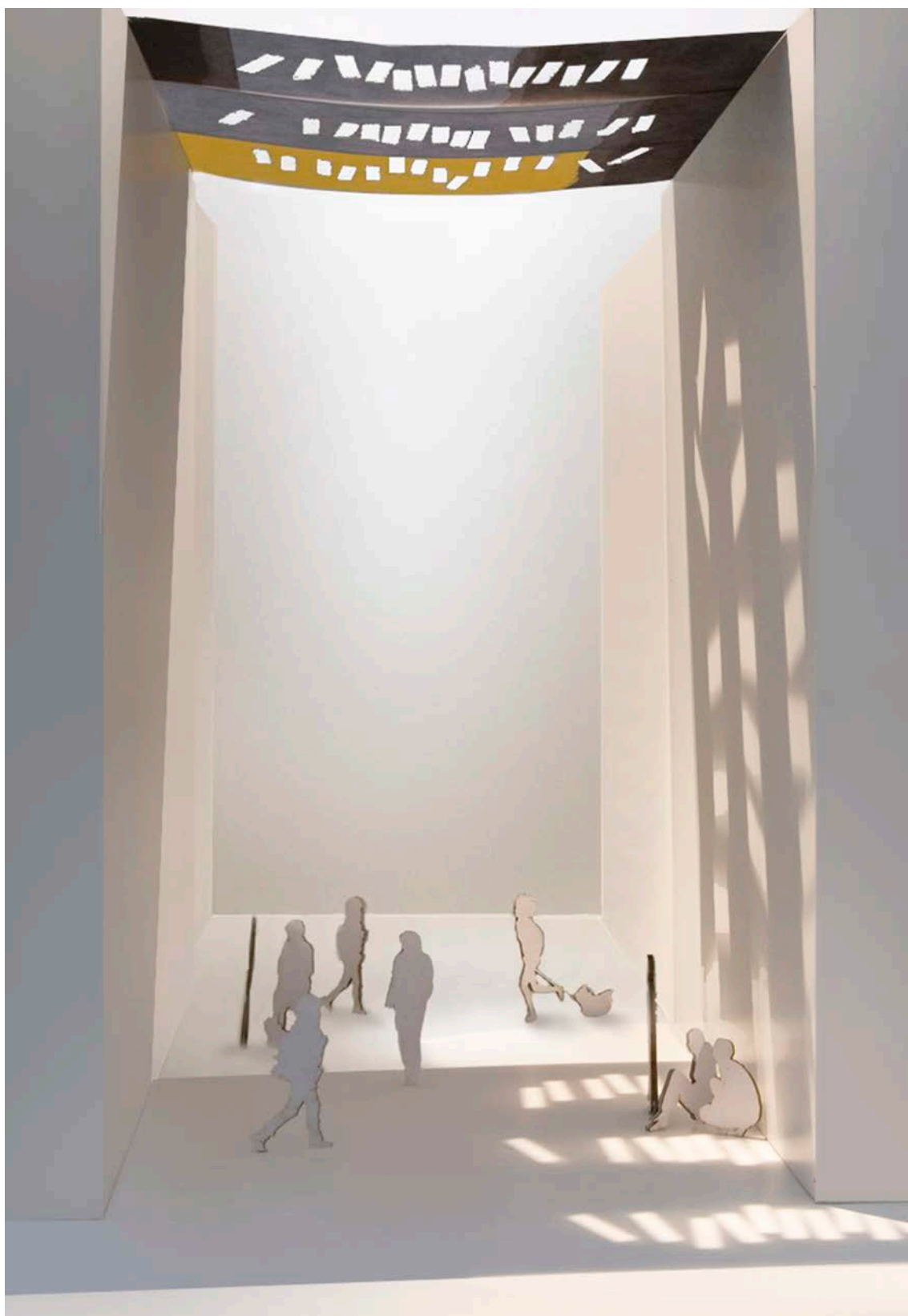
We have taken this as a base to develop a conceptual

application for the future. This project has been based on a real street scenario, however it has been investigated on scale model.

DESIGN SCENARIO

LAT.:37,23, LONG.: -5,58. South of Spain. Seville. Calle Sierpes. It is summer and heat is trapped in the city. Hot, dusty air makes it, at times, nearly impossible to breathe and the sun is burning down on the ground. Horses, Feriar. Flamenco. Wide avenues and narrow streets. The river. Abanicos, the typical traditional fans, waving in the hands for a flow of air. Light - a lot of bright light. Laughter. People buzzing around. Shopping malls. The heart of Andalucía. The Calle Sierpes is covered with sun sails. What a relief. No burning sun on your head anymore creating a play of light- and shadows on the flow of people in the street. Life is pulsing in and out of the boutiques in one of the most popular shopping streets of the city.





DESIGN PROCESS

The starting point of the project has been to use Seville as a scenario to base our observations and explorations in.

A mood board has been created to define the atmosphere in the selected environment. Words and visuals described the mood; happiness, 'A sunny day', alive, 'lived in', housing environment, traces of living, fragility, rhythm, movement, pulse, etc.

Based on the mood board, basic forms have been selected. Over 200 sails with forms/shapes/patterns have been created using laser cutting technology.

A simplified 3D model of a street section has been built, in which the sun sails have been displayed.

The sun laboratory at The Royal Danish Academy of Fine Arts, School of Architecture in Copenhagen has been used to investigate the sun sails in the 3D model under an artificial sun. The artificial sun creates light and shadow patterns in a street environment during a 24 hour sun path simulation. The main focus has been to observe the changes of the light and shadow patterns in the street environment, created using various sun sail patterns.

The design process and results have been documented, analysed and evaluated.

Thereupon more complex pattern compositions have been developed based on the newly defined design criteria created for this project.

At the second visit to the daylight laboratory in Copenhagen more complex pattern compositions have been tested. The light and shadow play during a 24 hour period from two pattern compositions have been made into animations.

The results have been documented, analysed and evaluated. The results have been formulated in the shape of animations, photos, graphic material and text.

EXHIBITION

The designer can no longer *just* develop a pattern composition on a 2D surface. The scenario shows that the challenge of the designer is to visualize the coexistence of a three dimensional pattern in space. What will this look like? To what extent can the design be predicted? Or will it be completely unpredictable?

Through experiments and observations we have tried to develop design dimensions, variables, required whilst working with this type of scenario.

Parts of our process and findings will be presented and highlighted in an installation based on eight objects:

The first object is an interactive 3D model of an abstract street. The street is equipped with sun sails and people. The audience can interact with the model. With the aid of a strong spotlight, it will possible to hold and subsequently twist the model in order to observe the

moving light and shadow patterns in the street during a 24 hour period. The model can be set-up for any specific day in the year using a mounted sundial diagram.

The second and third objects are two animated films which show two different pattern compositions – one emphasizing a pattern along the street and the other a pattern across the street through a 24 hour sun path. The sun sails will create constantly moving light and shadow patterns in the street scenario.

The fourth to ninth objects are storyboards which contain; an introduction to the project, the main conceptual ideas, illustrated documentation of the design process and results, as well as instructions for how to interact with the model.

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BARBARA JANSEN
The Swedish School of Textiles
University of Borås
barbara.jansen@hb.se

MARIE LEDENDAL
School of Textile and Design
Heriot-Watt University
mkl4@hw.ac.uk

Images previous pages: Daylight laboratory: moving artificial sun,
Daylight laboratory: observing the model, Photo: Henrik Bengtsson.
Film stills Animations_1 / Animations_2. This page: Daylight
laboratory: set up for animation films, Photo: Pierre Ledendal



Appendix G Conference paper - Thermochromic Dyes and Sunlight Activating Systems: an alternative Means to Induce Colour Change

Thermochromic Dyes and Sunlight Activating Systems: an Alternative Means to Induce Colour Change

Marie LEDENDAL,¹ Robert CHRISTIE,¹ Samantha VETTESE FORSTER²

¹ School of Textiles and Design, Heriot-Watt University

² School of Art and Creative Industries, Edinburgh Napier University

colour technology

ABSTRACT

Thermochromic leuco dyes may be applied to textiles substrates to provide colour change when the temperature is raised. These materials have been used previously by designers in interesting ways, activated with a variety of heat sources. This paper presents the outcome of research developing a set of 'design variables' appropriate for textile designers, for use with thermochromic textiles when activated by sunlight. Sunlight has the potential to provide a sustainable alternative means to induce colour change compared with the variety of electrical heating mechanisms that have previously been explored which are more controllable but energy intensive. The use of sunlight as the direct heat source was investigated for sun-screening textiles, for use either externally in an urban environment or in indoor window applications. Observations of sunlight-activated textiles led to identification of the significant colour change design variables as: amount of sunlight, time interval, rhythm, contact surfaces, ambient temperature and distribution of sunlight.

1. INTRODUCTION

Thermochromic leuco dyes change from coloured to colourless when the temperature is raised. This dye type consists of three components: colour former, acid activator and low melting solvent, microencapsulated so that the chromic system is protected by a walled structure. Mixing the chromic dyes with permanent pigments provides colour change between two colours (Christie, Robertson and Taylor 2007, p.2-3). Thermochromic dyes are characterised by an activation temperature at which most of the colour change takes place, although in reality the change is observed over a range of temperatures (LCR Hallcrest accessed 2010). A number of notable designers have experimented with the use of thermochromic materials, aiming to exploit the dynamic colour change properties. Most commonly, they have used electrical heating mechanisms to activate the dyes for fashion and interior textile design applications (Seymour 2008). These designers include Orth and International Fashion Machines (Seymour 2008, p.75), XS Labs (Berzowska and Bromley 2007, p.2), Worbin (Worbin 2010, p.146) and Berzina (Seymour 2008, p.183). This paper describes preliminary research using a novel approach to thermochromic dye activation in which natural sunlight is used to induce the colour change. The research has investigated the effects observed when the sun is the direct activating heat source, aimed at the design of sun-screening textiles that contain printed thermochromic elements. Carefully conducted observations have led to the formulation of a set of design variables for use in designing with thermochromic dyes and sunlight. Comparisons are made, from the perspective of the textile printmaker practitioner, between the principles involved in printed thermochromic textiles that are sunlight-activated and those activated by electrically-powered heaters.

2. METHOD

The research described in this paper involved systematic observations to investigate the colour change of thermochromic textiles activated by the sun in relation to the prevailing weather conditions. Thermochromic dyes with activation temperatures in the range 20–47°C were screen printed as single colours, in some cases combined with permanent pigments, on to a range of textile substrates with different thicknesses. In order to describe the sun conditions during the observations, two conditions were selected from the ‘Lighting Design Glossary’ (Lighting Design and Simulation Knowledgebase accessed 2011). To simplify the analysis, these two descriptions were re-defined as: ‘sunny sky’ containing 0–15% clouds, and ‘cloudy sky’ containing 25–80% clouds.

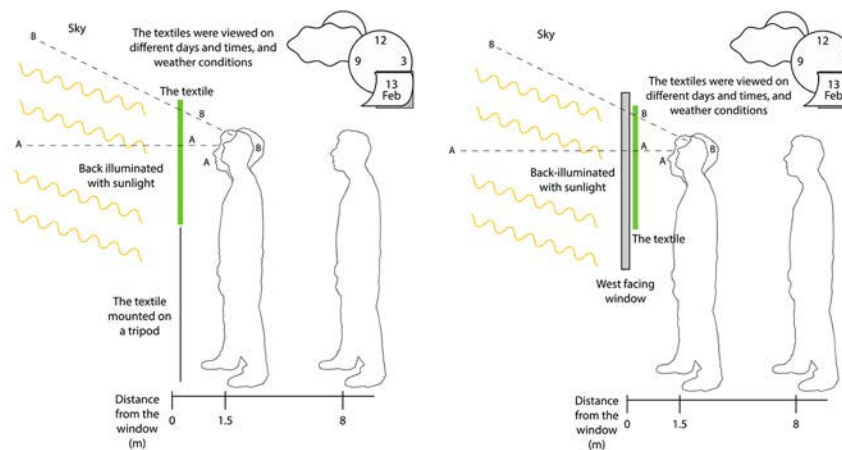


Figure 1: Set-ups used A and B for textile sample observations, indoors as well as outdoors.

Standard viewing methods, as illustrated in Figure 1, were devised for visual observation of the printed fabrics carried out to develop an understanding of the influence of the sunlight on the colour outcome for two different scenarios: indoor and outdoor situations. The observations were aimed at establishing relationships between the perceived colour of the fabric samples and the two sky conditions, when sunlight passed through the samples (referred to as back-illuminated). The observations were carried out in two geographic locations: Scottish Borders, UK and Scania region (Skåne), Sweden. For the indoor observations, the samples were mounted on a windowpane, whereas for outdoor observations the samples were mounted on a tripod (Figure 1). The ambient temperature indoors was mainly in the range 20–22°C. Most observations outdoors were carried out during summer, with ambient temperatures in the range 13–18°C. The results were assessed in terms of the impact of sunlight on the appearance of the printed textiles. A comparison was made of features involved in using sunlight and electrical heating sources to activate the thermochromic textiles in terms of their effectiveness and their limitations based on literature review and the author’s previous experience with chromic materials.

3. RESULTS AND DISCUSSION

The investigation led to the development of a set of design variables for use with thermochromic dyes activated by sunlight, presented in the context of textile design practice. The design variable ‘amount of sunlight’ illustrates the importance of the presence of sunlight and its random nature arising from weather variations. Observations demonstrated that the dynamic colour change behaviour of the printed samples depended on their placement (free-hanging or towards a contact surface), the level of sunlight and the weather including the sky conditions and the ambient temperature. The design variable ‘ambient temperature’ is determined by the environment in which the sun-screening textile is located, including time of day and geographical location. The design variable ‘time interval’ was addressed by devising two specific definitions, illustrated schematically in Figure 2: (a) the time taken for the chromic dye to achieve colour change (t_1), and (b) the time during which the chromic dye remains either in its active (t_2^a) or inactive (t_2^i) state, in each case as the sun comes and goes. The definition of t_1 is the time it takes for the dye to change colour either from being inactive (colour state 1) to being active (colour state 2) or vice-versa. The time taken for the printed samples to reach a state of all-over colour change differed depending on the relationship between the thermochromic activation temperature and the ‘internal heat coefficient’ (h_i) of the window surface (Karlsson 2001, p.5). The time for colour change due to heating by the sun, which varied from minutes to more than one hour, also depended on the environment, in turn influenced by the solar energy transmission through the window (Karlsson 2001, p.14).



Figure 2: Visualisation of the definitions of the design variables t_1 and t_2 .

The variable ‘rhythm’ involves a combination of the length of time between successive activations and deactivations and the time in the active and inactive states. The rhythm of the colour change is weather dependent; a constant sky creates a slower tempo while alternating weather conditions leads to a quicker tempo. The design variable ‘contact surface’ defines the impact of close-touching surfaces on the activation of colour change. Contact surfaces, both indoors and outdoors, facilitate activation the dyes, as well as increasing the rate of colour change. The variable ‘distribution of sunlight’ determines the illuminated activated areas of the textile, as well as the heat spread through the samples. The pattern of colour change demonstrated that this process started mainly at the centre of the fabric spreading towards the edges. When sufficient heat was generated by the sunlight, all of the illuminated areas printed with the thermochromic dyes displayed colour change.

A comparison of sunlight and electrical heating solutions, based on theoretical and experiential considerations, identified that the sun provides certain technical advantages, as well as the obvious energy-related environmental and sustainability advantages. Direct sunlight will more readily change the colour of larger printed areas with no need for additional application features. Complex heating circuitry with high energy demand would be required to produce sufficient heat over the surface (Robertson et al. 2008, p.27). There are design limitations, but also potential advantages, due to the random, unpredictable nature of sun-

light activation in terms of the time and level of available sunlight, and its dependence on weather conditions. In contrast, electrical circuitry integrated into textile applications may be optimised to regulate the heating, with the potential to use computer-based methods to control energy flow, and thus the temperature profile, in order to provide control of the colour change (Robertson et al. 2008, p.30).

4. CONCLUSIONS

A series of design variables have been identified to provide a tool for use by textile printmaker practitioners in design applications, for example in sun-screening textiles that incorporate printed thermochromic dyes and use sunlight as an activator.

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Address: MA. Marie Ledendal, School of Textiles and Design,
Heriot-Watt University, Scottish Borders Campus, Galashiels, TD1 3HF, UK
E-mail: mkl4@hw.ac.uk