Conceptual thermal design

PROEFSCHRIFT

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Ruben STRIJK

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Dit proefschrift is goedgekeurd door de promotor:
Prof.dr.ir. J.C. Brezet

Samenstelling promotiecommissie:

Rector Magnificus: Voorzitter
Prof.dr.ir. J.C. Brezet: Technische Universiteit Delft, promotor
Prof.dr.ir. M. Baelmans: Katholieke Universiteit Leuven
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## Contents

1 Introduction 11
   1.1 Thermal design 12
   1.2 Background 12
   1.3 Problem statement 13
   1.4 Methodology 15
      1.4.1 Nature of the research 16
      1.4.2 Research methods 16
      1.4.3 Scientific criteria 18
   1.5 Overview of the thesis 19

2 Thermal design, theory and tools 21
   2.1 Introduction 22
   2.2 What is thermal design 22
      2.2.1 General thermal design 22
      2.2.2 Thermal design in the product creation process 24
   2.3 General heat transfer theory 25
      2.3.1 Conduction 26
      2.3.2 Convection 26
      2.3.3 Radiation 27
      2.3.4 Thermal resistor/capacitor networks 27
      2.3.5 Compact thermal models 28
   2.4 Analysis and simulation 28
      2.4.1 Correlations and spreadsheet models 29
      2.4.2 Flow network modeling 31
      2.4.3 Computational fluid dynamics 31
      2.4.4 Finite element analysis 32
2.5 Thermal design techniques .............................................. 32
  2.5.1 Cooling fins ...................................................... 33
  2.5.2 Fans - forced convection ......................................... 33
  2.5.3 Heat pipes ....................................................... 33
  2.5.4 Thermoelectric coolers ........................................... 34
  2.5.5 Micro-channel heat exchangers .................................. 34
  2.5.6 Embedded electronic components ................................. 34
  2.5.7 Structural concept optimization .................................. 34
  2.5.8 Power management ................................................ 36
  2.5.9 Thermal management .............................................. 37
  2.6 Electronics reliability ............................................... 38
  2.7 Literature relevant to conceptual design ............................ 39
  2.8 Conclusions .......................................................... 40

3 Thermal design in practice ............................................. 41
  3.1 Introduction .......................................................... 42
  3.2 Approach ............................................................. 42
  3.3 Results of the interviews ............................................ 44
    3.3.1 The variety of development processes .............................. 44
    3.3.2 The practice of thermal design .................................... 47
    3.3.3 Problems from a practical point of view .......................... 57
    3.3.4 The need for easy-to-use formulas .................................. 57
  3.4 Interpretation and conclusion ....................................... 58

4 Design model 1 ............................................................ 61
  4.1 Introduction .......................................................... 62
  4.2 An approach for model 1 .............................................. 62
  4.3 The passive cooling limit of a product ............................... 63
    4.3.1 Model definition .................................................. 63
  4.4 Measurement results .................................................. 64
    4.4.1 Experimental method .............................................. 64
    4.4.2 Power and area measurement results ............................... 65
    4.4.3 Hotspot temperature measurement results ........................ 67
  4.5 Discussion ............................................................ 67
  4.6 How to apply model 1 in design ..................................... 68
  4.7 Conclusions and recommendations .................................... 70

5 Design model 2 ............................................................ 71
  5.1 Introduction .......................................................... 72
  5.2 Approach of model 2 .................................................. 73
  5.3 Model development .................................................... 73
    5.3.1 Description of the thermal RC-network ............................. 73
    5.3.2 Deriving state space equations .................................... 76
  5.4 Results .............................................................. 77
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4.1 Deriving heat transfer coefficients</td>
<td>78</td>
</tr>
<tr>
<td>5.4.2 Solving state space equations</td>
<td>79</td>
</tr>
<tr>
<td>5.4.3 Measurements on an AC-DC converter</td>
<td>80</td>
</tr>
<tr>
<td>5.5 Discussion</td>
<td>81</td>
</tr>
<tr>
<td>5.5.1 Highlights and implications</td>
<td>82</td>
</tr>
<tr>
<td>5.5.2 Computation of $\theta_2$</td>
<td>83</td>
</tr>
<tr>
<td>5.5.3 Computation of $\theta_4$</td>
<td>83</td>
</tr>
<tr>
<td>5.6 How to apply model 2 in design</td>
<td>84</td>
</tr>
<tr>
<td>5.7 Conclusions and recommendations</td>
<td>85</td>
</tr>
<tr>
<td>6 Design model 3</td>
<td>87</td>
</tr>
<tr>
<td>6.1 Introduction</td>
<td>88</td>
</tr>
<tr>
<td>6.2 Approach of model 3</td>
<td>88</td>
</tr>
<tr>
<td>6.3 Model definition</td>
<td>89</td>
</tr>
<tr>
<td>6.3.1 Model description</td>
<td>90</td>
</tr>
<tr>
<td>6.3.2 Exploring the general equation</td>
<td>90</td>
</tr>
<tr>
<td>6.4 Thermocouple measurements</td>
<td>93</td>
</tr>
<tr>
<td>6.4.1 Method</td>
<td>94</td>
</tr>
<tr>
<td>6.4.2 Results and discussion</td>
<td>94</td>
</tr>
<tr>
<td>6.5 Infrared thermography measurements</td>
<td>98</td>
</tr>
<tr>
<td>6.5.1 Method</td>
<td>99</td>
</tr>
<tr>
<td>6.5.2 Results and discussion</td>
<td>99</td>
</tr>
<tr>
<td>6.6 How to apply model 3 to a design</td>
<td>100</td>
</tr>
<tr>
<td>6.6.1 Example</td>
<td>101</td>
</tr>
<tr>
<td>6.7 Interpretation and conclusion</td>
<td>104</td>
</tr>
<tr>
<td>7 Evaluation through experiments</td>
<td>105</td>
</tr>
<tr>
<td>7.1 Introduction</td>
<td>106</td>
</tr>
<tr>
<td>7.2 Goal</td>
<td>106</td>
</tr>
<tr>
<td>7.3 Pilot study</td>
<td>107</td>
</tr>
<tr>
<td>7.4 Experiment design</td>
<td>108</td>
</tr>
<tr>
<td>7.5 Results</td>
<td>110</td>
</tr>
<tr>
<td>7.6 Interpretation and conclusion</td>
<td>113</td>
</tr>
<tr>
<td>8 Evaluation through interviews</td>
<td>119</td>
</tr>
<tr>
<td>8.1 Introduction</td>
<td>120</td>
</tr>
<tr>
<td>8.2 Goal and approach of the interviews</td>
<td>120</td>
</tr>
<tr>
<td>8.3 Results</td>
<td>122</td>
</tr>
<tr>
<td>8.3.1 Criterion 1: Applicability</td>
<td>122</td>
</tr>
<tr>
<td>8.3.2 Criterion 2: Efficiency</td>
<td>123</td>
</tr>
<tr>
<td>8.3.3 Criterion 3: Quality</td>
<td>124</td>
</tr>
<tr>
<td>8.3.4 Criterion 4: Propositions</td>
<td>125</td>
</tr>
<tr>
<td>8.3.5 Criterion 5: Improvements</td>
<td>126</td>
</tr>
<tr>
<td>8.3.6 Criterion 6: Generality</td>
<td>127</td>
</tr>
</tbody>
</table>
CONTENTS

8.4 Comparison and conclusion ........................................ 127

9 Conclusions and recommendations ................................. 131
  9.1 Introduction .......................................................... 132
  9.2 Answer to the main question ...................................... 132
  9.3 Scientific relevance of the approach ........................... 133
  9.4 The generality of the models and methods .................... 133
  9.5 Recommendations for future research ......................... 134

A Protocol used to interview experts ................................ 137

B Euler algorithm .......................................................... 141

C Function for unconstrained minimization ......................... 143

D Protocol used to conduct the usability experiment .......... 145

  Nomenclature ................................................................ 155

  Summary ....................................................................... 157

  Samenvatting .................................................................. 159

  Acknowledgements ........................................................ 161

  Curriculum Vitae .......................................................... 163
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Moore’s Law for intel processors.</td>
<td>13</td>
</tr>
<tr>
<td>1.2</td>
<td>Chip trends.</td>
<td>14</td>
</tr>
<tr>
<td>1.3</td>
<td>Research design.</td>
<td>15</td>
</tr>
<tr>
<td>1.4</td>
<td>Thesis overview.</td>
<td>20</td>
</tr>
<tr>
<td>2.1</td>
<td>Packaging levels in electronic product design.</td>
<td>23</td>
</tr>
<tr>
<td>2.2</td>
<td>Overview of thermal design techniques.</td>
<td>24</td>
</tr>
<tr>
<td>2.3</td>
<td>General and enhanced thermal design cycle.</td>
<td>25</td>
</tr>
<tr>
<td>2.4</td>
<td>Flow chart for a semi-empirical design of electronic equipment.</td>
<td>30</td>
</tr>
<tr>
<td>2.5</td>
<td>Thermal design techniques.</td>
<td>33</td>
</tr>
<tr>
<td>3.1</td>
<td>General product design process.</td>
<td>44</td>
</tr>
<tr>
<td>3.2</td>
<td>Design processes from interviews.</td>
<td>46</td>
</tr>
<tr>
<td>4.1</td>
<td>Existing products and theoretical cooling limits.</td>
<td>65</td>
</tr>
<tr>
<td>4.2</td>
<td>Examples of hotspot measurements.</td>
<td>66</td>
</tr>
<tr>
<td>4.3</td>
<td>Hotspot temperature in relation to the ratio power/area.</td>
<td>67</td>
</tr>
<tr>
<td>4.4</td>
<td>Model 1.</td>
<td>69</td>
</tr>
<tr>
<td>5.1</td>
<td>Thermal resistor capacitor network model 2.</td>
<td>74</td>
</tr>
<tr>
<td>5.2</td>
<td>Overview of an AC-DC adaptor.</td>
<td>76</td>
</tr>
<tr>
<td>5.3</td>
<td>Measured and computed temperatures for 1W and 2W.</td>
<td>79</td>
</tr>
<tr>
<td>5.4</td>
<td>Steady-state temperatures of the adaptor.</td>
<td>80</td>
</tr>
<tr>
<td>5.5</td>
<td>Measurement and improved model results for 1W dissipation.</td>
<td>81</td>
</tr>
<tr>
<td>5.6</td>
<td>Numerical solver ‘Thermanizer’.</td>
<td>85</td>
</tr>
<tr>
<td>5.7</td>
<td>Graphs produced by ‘Thermanizer’.</td>
<td>86</td>
</tr>
<tr>
<td>Figure Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6.1</td>
<td>Thermal resistor-capacitor network.</td>
<td>89</td>
</tr>
<tr>
<td>6.2</td>
<td>Several mock-up configurations.</td>
<td>91</td>
</tr>
<tr>
<td>6.3</td>
<td>Mock-up measurement setup.</td>
<td>93</td>
</tr>
<tr>
<td>6.4</td>
<td>Temperature differences from the hotspot to ambient environment.</td>
<td>95</td>
</tr>
<tr>
<td>6.5</td>
<td>Temperature differences of the average encasing to an ambient environment.</td>
<td>96</td>
</tr>
<tr>
<td>6.6</td>
<td>Temperature differences for maximum and average encasings.</td>
<td>97</td>
</tr>
<tr>
<td>6.7</td>
<td>Results of the IR experiment.</td>
<td>99</td>
</tr>
<tr>
<td>6.8</td>
<td>3D results of the IR experiment.</td>
<td>100</td>
</tr>
<tr>
<td>6.9</td>
<td>Comparison of measurements and predictions for configuration A with a 0,5W power dissipation.</td>
<td>101</td>
</tr>
<tr>
<td>6.10</td>
<td>Comparison of measurements and predictions for configuration A, B, C, D, E and F.</td>
<td>103</td>
</tr>
<tr>
<td>7.1</td>
<td>Product contents.</td>
<td>107</td>
</tr>
<tr>
<td>7.2</td>
<td>Observational set-up of the experiment.</td>
<td>109</td>
</tr>
<tr>
<td>7.3</td>
<td>Applicability evaluation of models 0-3.</td>
<td>111</td>
</tr>
<tr>
<td>9.1</td>
<td>Example of an improved visualization of an RC-network.</td>
<td>135</td>
</tr>
</tbody>
</table>
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Literature related to conceptual thermal design.</td>
<td>39</td>
</tr>
<tr>
<td>3.1</td>
<td>Participants from preliminary interviews.</td>
<td>43</td>
</tr>
<tr>
<td>3.2</td>
<td>Typical thermal design criteria of a described case.</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>Problem versus solution scope.</td>
<td>50</td>
</tr>
<tr>
<td>3.4</td>
<td>Typical thermal design topics during development project.</td>
<td>53</td>
</tr>
<tr>
<td>3.5</td>
<td>Analysis and testing topics.</td>
<td>55</td>
</tr>
<tr>
<td>4.1</td>
<td>Natural convection and radiation heat transfer coefficients</td>
<td>63</td>
</tr>
<tr>
<td>5.1</td>
<td>Data for calculating $h_c$ and $h_r$.</td>
<td>78</td>
</tr>
<tr>
<td>5.2</td>
<td>Measurement and computation results.</td>
<td>82</td>
</tr>
<tr>
<td>6.1</td>
<td>Time constants.</td>
<td>97</td>
</tr>
<tr>
<td>6.2</td>
<td>Total thermal resistance</td>
<td>98</td>
</tr>
<tr>
<td>6.3</td>
<td>Thermal capacitance</td>
<td>98</td>
</tr>
<tr>
<td>6.4</td>
<td>Infrared results.</td>
<td>100</td>
</tr>
<tr>
<td>6.5</td>
<td>Variables and values used in predictions.</td>
<td>102</td>
</tr>
<tr>
<td>7.1</td>
<td>Participants in the usability experiment.</td>
<td>108</td>
</tr>
<tr>
<td>7.2</td>
<td>Experiment data.</td>
<td>112</td>
</tr>
<tr>
<td>7.3</td>
<td>Evaluation of model 0.</td>
<td>114</td>
</tr>
<tr>
<td>7.4</td>
<td>Evaluation of model 1.</td>
<td>115</td>
</tr>
<tr>
<td>7.5</td>
<td>Evaluation of model 2.</td>
<td>116</td>
</tr>
<tr>
<td>7.6</td>
<td>Evaluation of model 3.</td>
<td>117</td>
</tr>
<tr>
<td>7.7</td>
<td>De-briefing questionnaire for perceived usability.</td>
<td>118</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>8.1</td>
<td>General evaluation questions</td>
<td>121</td>
</tr>
<tr>
<td>8.2</td>
<td>Evaluation of criteria with regards to model 1</td>
<td>128</td>
</tr>
<tr>
<td>8.3</td>
<td>Evaluation of criteria with regards to model 2</td>
<td>129</td>
</tr>
<tr>
<td>8.4</td>
<td>Evaluation of criteria with regards to model 3</td>
<td>130</td>
</tr>
<tr>
<td>D.1</td>
<td>Usability experiment screenplay</td>
<td>145</td>
</tr>
</tbody>
</table>
The present chapter will introduce the topic of this dissertation, thermal design in the conceptual phase of product development. After reading this chapter, the main research question concerning approach and social relevance will be addressed and developed.
1.1 Thermal design

This thesis deals with the thermal design of electronic products during the conceptual phase of product development. In the context of this thesis, an electronic product is defined as a mechanical encasing containing one or more electronic circuits that fulfill one or more functions. An electronic circuit can contain both active and/or passive electronic components, such as resistors, inductors, capacitors, transistors, integrated circuits, and so on. The electronic circuit generally dissipates a certain amount of heat, which should be taken into account during the design process. In this chapter, the following question will be answered: What is the problem and how are we going to solve it?

With the increasing amount of transistors per $cm^2$ present in semi-conductors, temperature is becoming an important issue in the design of electronic products. If the thermal design is not proficient, then reliability becomes a problem. When the temperature rises too high, the lifetime of a product can be significantly reduced and safety issues arise.

Often, designers developing the structural design and mechanical encasing of electronic products must deal with this issue. Generally, the earlier one begins solving a design problem, the quicker and more efficiently it can be solved. This is important because time invested in product development is decreasing. In addition, the power density of components and printed circuit boards is increasing to higher levels.

At this time, designers are mainly dependent on either their own tacit knowledge or knowledge of thermal experts, handbooks and, at times, computational fluid dynamics software. However, it would be more convenient to have access to simple general models during the conceptual phase to estimate the temperature in a device and help improve cooling.

1.2 Background

Energy consumption is generally seen as an important problem in society. The main reason for this is the emission of $CO_2$ to the environment through the process of generating energy through burning oil and coal. This process is generally seen as the main cause of global warming and has been an item for discussion since Svante Arrhenius published his paper “On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground” [1]. In politics, this issue has been intensely discussed during the last few years. In engineering, the issue has become intensified by the publishing of one of the most significant studies conducted in this field: “The limits to growth; a report for the Club of Rome’s project on the predicament of mankind” [45]. The Kyoto protocol on $CO_2$ reduction, signed by 168 countries on April 18th, 2006, can be seen as one of the most significant directions towards change in this field.

Electronic products used in society today consume a significant amount of energy, which is partly induced by manufacturing and end-of-life consumption, but most significantly by use. In total, energy use accounts for 50-80% of the total environmental impact of electronic products [7]. In electronic products, optimal thermal management
1.3. PROBLEM STATEMENT

Thermal design is the main issue concerning design engineers with regards to energy consumption in electronic products. A good thermal design concept is important be-
CHAPTER 1. INTRODUCTION

Figure 1.2: Left: Historical and future trends of the chip and circuit and the transistor level power density of mainstream microprocessors. Right: Characteristic length scales of components of a microprocessor [69].

cause it improves the reliability and functionality of an electronic product. In addition, international regulations define safety requirements for electronic equipment, including maximum encasing temperature and the maximum size allowed for ventilation holes in the encasing [27, 26]. Therefore, heat transfer within a product significantly influences the structural concept that must be defined during the conceptual stage. That is why the focus of this thesis is on models and methods that support this stage in design.

The time-to-market time period is shortened so that in product development there is an increasing focus on the product development speed [59]. As a consequence, there is less time to develop reliable, high-quality products. In addition, the amount of electronics around us, ubiquitous electronics [68], is increasing at a rapid speed. With the increasing power density of electronic products, thermal design creates a bottleneck in the development process. Therefore, it becomes necessary to provide electronic engineers and mechanical/design engineers with models and methods which take temperature into account during the conceptual phase of design [49]. Such an approach can prevent thermal design bottlenecks from showing up during a project’s conclusion and results in a shorter design cycle.

Many tools and techniques are available for thermal design. Examples include heat pipes, conductive fillers, water cooling, micro-heat exchangers and advanced computational fluid dynamics (CFD) software. Although these developments have led to the improvement of thermal designs, most designers still do not know how to compute simple temperature approximations. As a result, their design decisions are mainly based on experience. The aim of this project is to provide thermal design tools for industrial designers who are not specialists in thermal design. Furthermore, the aim is to give them a solid base for discussing thermal design problems with a thermal design specialist. In
1.4 Methodology

The research question proposed in the previous paragraph must be explored through a research methodology that will fulfill research criteria, such as validity and reliability. With this methodology, it is necessary to propose a research design that fits the nature of this project, the objective is to explore the possibilities of developing easy-to-use thermal design models and make the existing body of knowledge of thermal design more accessible for industrial design engineers. In this project, we propose the following general research question:

**How can the thermal design of electronic products be optimized during the conceptual phase of product development?**
the research.

1.4.1 Nature of the research

Over the last few decades, the research area of thermal design has been extensively studied. Although the following chapters will outline existing research focused on design engineers, thermal design can generally be characterized as research that mainly focuses on the thermal design specialist. Research, similar to that described in this thesis, can therefore be characterized as explorative, searching for new concept directions that will improve thermal design for industrial designers. In addition, it would be most appropriate to speak of theory development research as opposed to theory/hypothesis testing research.

Although a variety of research methods is used during the specific phases of this project, the general study is closely linked to the design engineering process. This is not unusual, considering that the author has a background in designing approaches taught by the faculty of Industrial Design Engineering in Delft. This approach focuses on a methodology that begins with the definition of the problem and results in practical and applicable solutions. An overview of the research design of this thesis is shown in figure 1.3.

1.4.2 Research methods

As can be seen in figure 1.3, this thesis contains four main phases that attempt to answer the main research question. In this section, this approach will be further explored. The project in general can be seen as an explorative case study. According to the theory of explanation building [8], the process is iterative; the case study presented here should be regarded as an initiation and a basis for future case studies in the field of thermal design.

During the preliminary phase, the research question is analyzed by studying scientific literature and in-depth interviews with designers from the industry. Explorative research, such as that presented in this thesis, is used to form an hypothesis. The main question can be answered by defining propositions to three main problems in the field:

1. Many designers are unfamiliar with heat transfer theory and thermal design.
2. An evaluation of structural concepts on temperature development is not supported by a standard approach.
3. Temperature measurements on mock-ups and functional models are crucial for thermal design in practice in order to find reliable heat transfer coefficients, but are time-consuming to develop.

The second phase is model development, which results in solutions. These solutions consist of three models and methods of practical application that will be developed and evaluated with regards to their use in the design process. The basic idea behind this approach comes from mechanical engineering, where there is an extensive amount of
1.4. METHODOLOGY

formulas and methods used to complete a mechanical analysis in the conceptual design [55]. The models and methods that will be developed and tested focus on different problems associated with thermal analysis in the conceptual design stage. For this thesis, the following definitions for the words “model” and “method” will be used:

Model is a mathematical description of the heat transfer process in an electronic product. The model can be represented in the form of a graph or software program.

Method is a particular procedure used to apply a model to a design problem.

Model 1 will be the first model described in this thesis and will focus on a basic question in thermal design: Is active or passive cooling involved? The model is developed based on theoretical heat transfer approximations and empirical measurements. Although this model does not give an explicit temperature, it is a semi-empirical approach for evaluating designs and determining how important thermal design will be in the project.

The second approach described in this thesis is the development of a generic model that can be used to approximate or model transient temperature development of the heat path in a product. Model 2 is based on the numerical computation of a thermal resistor/capacitor network (RC-network) and results in transient temperature approximations of the hotspot and encasing. The model can be used before temperature is measured by means of a full-working model or a thermal mock-up.

The third model, model 3, is developed as an interactive model. It results from the assumption that because full-working models or thermal mock-ups are almost always developed during the product development process to check the thermal concept, combining these measurements with a simple model to speed up the measurement process and give better directions, would allow designers to choose the most viable solution. Model 3 is based on the theoretical derivation of an RC-network, which is extended for various product configurations.

Developing these models is one thing, but more important and often lacking in many technical studies is the actual evaluation of the models in practice. Therefore, in the third phase of this project, usability will be evaluated by applying the three models to a usability experiment. Although other criteria are also discussed, the three following will be most important:

Criterion I: Applicability Are the presented methods practical and applicable for industrial designers engaging in the design process?

Criterion II: Efficiency Does applying the present models improve the efficiency of the design process of electronic equipment?

Criterion III: Quality Does applying the present models increase the quality of electronic products?

The final phase of this research encompasses the falsification of model 1, model 2 and
model 3. The terminology falsification is used here because the aim is to disprove the propositions by reflection on the research by design experts. This type of reflective science is suggested to improve the inter-subjectivity. It is suggested that openness be applied to opinions of experts or that peer debriefing be used to improve the construct validity of the results [8].

1.4.3 Scientific criteria

This is a case study. The research design must clarify how to fulfill scientific criteria. In this project, scientific criteria proposed by Braster are used. These include controllability, construct validity, internal validity, external validity and reliability [8].

The controllability of this research project is realized by documenting and collecting research data in a research database. The database contains results from individual research projects that have been executed and are available, with the exception of some confidential data, for review by others. The completed in-depth interviews and usability study are documented on digital audio or video means and have been transcribed for further analysis. In the case of the in-depth interviews and usability experiment, a research protocol has been developed to guide the semi-structured nature of these types of studies. When necessary, the research protocol and guiding questionnaires are listed in the appendix of this dissertation. In cases where this has not been completed, the material will be open for review.

Construct validity is a special issue in case study research, including the examples presented in this dissertation. In the present study, the initial problem definition and results of the usability evaluation are discussed during in-depth interviews at the end of the project. Participants in this final set of interviews have been selected from participants in primary interviews previously conducted. They have been determined as the most involved in the industrial manufacturing of electronic products. In this sense, this group functions as a member check, but also as a means of peer debriefing. In chapter 8, a section is devoted to a discussion on how these participants view the generality of the proposed models and the propositions on which the research is based.

In order to evaluate internal validity, the causal relation between dependent variables (usability, efficiency, quality) and independent variables (the three conceptual models) will be discussed in the final chapters of this study. The discussion will be based on pattern matching. Empirical patterns are two-dimensional and can be regarded as a means of triangulation. In the first case, the results of the usability study evaluate expectations between dependent and independent variables. In the second case, results from in-depth interviews determine the internal validity from an inter-subjectivity point-of-view through the reflection of experts interpreting research results.

For case studies, the main focus of external validity is theoretical generalization [71]. It is expected that generalizing results improves with increasing iterations. Since the present research project can be seen as a single case study, it must be clearly stated that the author does not intend to generalize the results. It is suggested that proceeding with the existing approach will improve generalization.
1.5. OVERVIEW OF THE THESIS

Reliability is a critical issue in case study research, especially when semi-structured interviews are used, for example, in the present project. In order to control reliability, guiding questions have been used in each of the respective interviews. In addition, the usability study follows a certain protocol. However, because of the flexible approach and continuous change of input and development of insights, reliability remains an issue. Because of this, results (video tapes, audio transcriptions, questionnaires, etc.) are available for review.

When researching the area of design engineering, the usability of developed tools is of special interest. From this viewpoint, a usability study has been included.

1.5 Overview of the thesis

This paragraph describes an overview of the thesis. The structure is displayed in figure 1.4. The chapters are grouped together in four sections.

The first section, preliminary research, describes the relevance of this work and explains how the proposed objectives will be achieved. This is done in chapter 2 through a review of research literature. Results show applications and possibilities for thermal design and show deficits from a scientific point of view. In chapter 3, in-depth interviews with designers from the field are used to explain the status of thermal design in practice, the problems at hand and possible directions for solutions.

The second section, model development, describes three different models and methods for determining thermal analysis in the conceptual stage of development. The section begins in chapter 4 with a description of the simplest thermal design model using only the estimated power and surface area of the minimum enclosed box of a product. In chapter 5, a generic theoretical model of an electronic product is described. The model gives a transient approximation of temperature based on easy-to-approximate design parameters, such as dimensions and material properties. Chapter 6 concludes with a simple formula that can be used to describe the transient temperature behavior of an electronic product. The model is combined with temperature measurements for a full-working model or thermal mock-up and can be used to quickly evaluate design changes in the product.

The third section, application and falsification, gives insight on how the proposed models and methods optimize the design process. Three primary aims are addressed in these chapters, including applicability, efficiency and quality. The proposed models and methods in chapter 7 are evaluated by means of a usability study. In chapter 8, they are evaluated through interviews with practicing designers.

The fourth section, titled “What’s next?”, closes the thesis with an overview of the results, conclusions and recommendations for further research.
**Preliminary research**

<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 2</td>
<td>Thermal design, Theory and tools</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Thermal design in practice</td>
</tr>
</tbody>
</table>

- What is the most basic and simple method that can be developed for first order thermal design, active vs. passive cooling?
- Which tools and techniques are described in literature and where are scientific studies focused on?
- What are the main problems from a practical point of view?

**Model development**

<table>
<thead>
<tr>
<th>Chapter 4</th>
<th>Design model 1: Evaluating active vs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 5</td>
<td>Design model 2: A generic resistor capacitor network</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Design model 3: A back of the envelope formula</td>
</tr>
</tbody>
</table>

- Can we make one generic model that can be used to theoretically estimate the temperature in the heat path in an electronic product?
- Can we develop a concept for formulas that can be used in combination with measurements on a full working model or thermal mock-up?

**Application and falsification**

<table>
<thead>
<tr>
<th>Chapter 7</th>
<th>Evaluation of the three models through</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 8</td>
<td>Evaluation of the three models through interviews</td>
</tr>
</tbody>
</table>

- What is the usability, efficiency and quality of the models?
- What do design experts think about it?

**What’s next?**

| Chapter 9 | Conclusions and recommendations |

- Has the objective been reached and where do we go from here?

Figure 1.4: Thesis overview.
CHAPTER 2

Thermal design, theory and tools

This chapter provides a review of thermal design theory and thermal design tools described in pertinent literature. The overview given in this chapter is a basis for an evaluation of thermal design in practice throughout the following chapters.

<table>
<thead>
<tr>
<th>Preliminary research</th>
</tr>
</thead>
</table>
| Chapter 1
  Introduction       | What is the problem and how are we going to solve it? |
| Chapter 2
  Thermal design, Theory and tools | Which tools and techniques are described in literature and where are scientific studies focused on? |
| Chapter 3
  Thermal design in practice | What are the main problems from a practical point of view? |
2.1 Introduction

The present chapter focuses on the question Which tools and techniques are described in literature and on what are scientific studies focused? This question is answered by describing the literature in the field of thermal design, including general heat transfer theory, analysis and simulation, thermal management techniques and electronics reliability.

In section 2.2, an overview is given of what thermal design actually is. Four main areas are identified and described. In section 2.3, general heat transfer theory is discussed. The section also describes the three main types of heat transfer, including conduction, convection and radiation. These types will be a basis for much of the mathematical models that are presented in chapters 4, 5 and 6. Section 2.4 describes the present state of development in the area of analysis and simulation. An overview is given of the methods available that would enable a designer to perform a thermal analysis. The section begins with a description of the analogue resistor/capacitor network theory and flow network modeling, followed by a description of the possibilities for computational fluid dynamics and finite element analysis. Section 2.5 reviews the basic techniques currently available enabling designers to optimize thermal design. A review is given on techniques generally used in electronic products, such as heat pipes, cooling fins, fans and other options, such as power management. Then, in section 2.6 a review of reliability is given, which is closely related to thermal design. The chapter finishes with an overview of research needs described in several significant papers in the field and conclusions from literature.

2.2 What is thermal design

This section explains the concept of thermal design, what is it, how it relates to the design process and which tools and techniques are available.

2.2.1 General thermal design

Thermal management is important for the reliability and durability of electronic products. The reason for this is that temperature influences expected component life through several failure mechanisms. Examples include increased leakage currents, oxide breakdown, electro migration, accelerated corrosion and increased material stress due to thermal expansion [6]. Controlling temperature is one of the four major functions of electronics packaging; the other three are mechanical support, interconnection and protection of the circuit. These major functions should be regarded on five packaging levels, which are shown in figure 2.1 [6].

The usability of electronic products is influenced by criteria with regards to the temperature of the encasing and, in cases of active cooling, on the temperature of the outgoing airflow. In addition, dust requirements limit the possibilities of cooling, especially in outdoor applications [58].
2.2. WHAT IS THERMAL DESIGN

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Total system level</td>
<td>Electronic product (e.g. laptop)</td>
</tr>
<tr>
<td>2) Sub-system level</td>
<td>Boards in enclosure (e.g. cd-rom drive)</td>
</tr>
<tr>
<td>3) Functional unit level</td>
<td>Board to board interconnection (e.g. soundcard in motherboard)</td>
</tr>
<tr>
<td>4) Sub-assembly level</td>
<td>Board (e.g. motherboard, videocard)</td>
</tr>
<tr>
<td>5) Component level</td>
<td>Electronic components (e.g. processor, resistors)</td>
</tr>
</tbody>
</table>

Figure 2.1: An overview of packaging levels in electronic product design [6].

Four main areas are of interest in the thermal design of electronic products. Figure 2.2 gives an overview of these four areas and includes the general heat transfer theory and power dissipation, analysis and simulation, thermal design tools and techniques and electronics reliability.

General heat transfer theory and power dissipation theory consist of the fundamentals of heat transfer, which include conduction, radiation and convection. In thermal design, these general modes of heat transfer are used to predict cases of interest, such as conduction within a package, natural and forced convection from a surface and the conductive removal of heat to a substrate or board.

The basic heat transfer equations for conduction, convection and radiation are used in combination with a thermal resistor/capacitor network (RC-network) to calculate temperature distributions. Examples of where RC-networks are applied can be found in methods such as flow network modeling (FNM) and in the definition of compact thermal models for integrated circuits. In handbooks, RC-networks are usually used to define practical solutions for such issues as heat sink design and air flow resistance.

In addition to the use of RC-networks, computational fluid dynamics (CFD) and finite element analysis (FEA) can be used to numerically solve partial differential equations of a geometrical problem divided into discrete cells (the mesh). Although these techniques are sometimes used by thermal design experts during the conceptual phase, they are generally regarded as tools that should be applied during detail design.

Several tools and techniques exist to optimize the thermal design of an electronic product. In general, these tools follow two principles. 1) First, it is necessary to transport heat away from a hotspot within a device in order to 2) dissipate the heat to an ambient environment. Heat transport is done by means of conductive fillers, heat pipes, etc. Power is then dissipated to the environment by means of convection (natural or forced) and radiation, often, through cooling fins or the encasing. Other cooling techniques exist, such as liquid cooling or vapor space condensers, but are not frequently used in consumer products.

Several thermal-related reliability approaches are described throughout literature. One of the most widely used standard work in reliability is MIL-HDBK-217 [17]. Although this handbook is widely used, it is also a concept that is relatively outdated. Better handbooks are available, such as Lall’s “Influence of Temperature on Microelectronics
1) Generation of heat dissipation and general heat transfer theory

<table>
<thead>
<tr>
<th>Conduction</th>
<th>Convection</th>
<th>Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steady-state conduction</strong></td>
<td>Natural convection and forced convection</td>
<td>The heat transfer coefficient of radiation can be derived from the general radiation heat transfer function: $q_r = \alpha F(T_2^4 - T_1^4)$ where $h_r = \alpha F(T_2^4 + T_1^4)(T_2 - T_1)$</td>
</tr>
<tr>
<td>1) Conduction in simple geometries</td>
<td>Analytical calculation of the heat transfer coefficient $h_c$ is very difficult. Therefore much attention is given to empirical and CFD determination of $h_c$. $\text{Nu}=h_c \cdot L/k_c$; $\text{Nu}=c \cdot Gr^n \cdot Pr^m$</td>
<td>CFD</td>
</tr>
<tr>
<td>a. Conduction through a plane wall</td>
<td><strong>CFD</strong></td>
<td>- Reynolds-averaged Navier-Stokes equations with turbulence model</td>
</tr>
<tr>
<td>b. Conduction through cylinders and spheres</td>
<td>- Direct numerical simulation</td>
<td>-</td>
</tr>
<tr>
<td>c. Plane wall with heat generation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Cylinders and spheres with heat generation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. Critical radius of a cylinder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Conduction in complex geometries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Multidimensional analytic method</td>
<td></td>
<td></td>
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<tr>
<td>b. Multidimensional graphical method</td>
<td></td>
<td></td>
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<tr>
<td>c. Multidimensional shape factor method</td>
<td></td>
<td></td>
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<tr>
<td>d. Finite difference method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. Resistor/capacitor networks</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transient conduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Lumped capacitance method</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2) Analysis and simulation

| Steady-state calculation methods: | | |
| - **Analytic:** Using differential equations (usually difficult to solve) | | |
| - **Analogical:** resistance networks ($\theta_0 = x/A$, $\theta_1 = 1/h_c A$; $\theta_1 = 1/(\alpha F(T_2^4 + T_1^4)(T_2 - T_1)A)$) | | |
| - **Graphical:** flux plot method/schmidt method | | |
| - **Numerical:** finite element method, finite volume method, finite difference method | | |

| Transient calculation methods: | | |
| - Lumped Capacitance Method | | |

Both analogical and numerical methods give relatively accurate results once the heat transfer coefficients are reliable.

3) Thermal management cooling techniques

- Cooling fin, fan, heatpipe phase change cooling, peltier element, conductive paste, gapfiller, etc.

4) Electronics reliability

- MIL-HDBK-217. Relative outdated reliability concept, however still used much in practice because of it’s long-time function as a standard work.
- Influence of Temperature on Microelectronics and System Reliability, (M.G. Pecht et al). Is in literature regarded as the most important ‘standard’ when it comes to reliability prediction.

Figure 2.2: Overview of thermal design techniques described in handbooks.

and System Reliability”, [40]. Additionally, directions for more comprehensive methods, such as physics of failure [60], have been introduced. An interesting overview of reliability techniques is given by Denson in his article, “The history of reliability prediction” [16].

2.2.2 Thermal design in the product creation process

Engineers want to develop optimal designs that meet requirement specifications for components and are developed within a reasonable range of time. With regards to thermal analysis, several tools can be used that have their own specific values within the design
2.3. GENERAL HEAT TRANSFER THEORY

In order to understand the area of thermal design, some background information on heat transfer is required. Therefore, at this point, it becomes necessary to introduce the basic theory surrounding heat transfer. A nomenclature of all symbols presented here and in the following chapters is given at the end of this thesis.

Three types of heat transfer exist and include conduction, convection and radiation. With conduction, the geometry of the heat path and the thermal conductivity $k$ are important. For convection and radiation, the heat transfer coefficient $h$ is an important parameter. $h$ is often difficult to predict and is usually the parameter that determines the accuracy of temperature calculations. The basic formulas for these three types of heat transfer will now be given.
2.3.1 Conduction

Conduction is the diffusion of heat through a material. In conduction heat transfer, the heat flow $q$ is a function of the thermal conductivity $k$ of a material, the cross sectional area $A$ and the temperature gradient $\delta T$, over a differential distance $\delta x$. The basic equation for conduction is as follows:

$$ q = -k \cdot A \cdot \frac{\delta T}{\delta x} \quad (2.3.1) $$

If, for a constant surface area $A$ and distance $x$, equation 2.3.1 is integrated, an equation is derived that describes the temperature difference $\Delta T$, in relation to the (one-dimensional) heat flow $q$. The $-$ sign on the right side of equation 2.3.1 indicates that temperature reduces in the direction of the heat flow. After integrating equation 2.3.1 over $x$, the following formula can be given:

$$ q = \frac{k}{x} \cdot A \cdot \Delta T \quad (2.3.2) $$

2.3.2 Convection

Convection heat transfer exists when a fluid flows along a surface and a difference in temperature occurs between the surface and the fluid. In electronics, cooling the fluid generally entails transferring air and heat from the (hot) surface by diffusing individual particles and through the motion of currents in the (cold) fluid. Although heat transfer through convection is very complex and nonlinear, the basic formulation of convective heat transfer is defined as a relatively simple linear equation. In convection heat transfer, the heat flow $q$ is a function of the convective heat transfer coefficient $h_c$, the convective surface area $A$ and the temperature difference between the surface temperature $T_s$ and the fluid temperature $T_f$. The general formula for convection is as follows:

$$ q = h_c \cdot A \cdot (T_s - T_f) \quad (2.3.3) $$

It is important to realize that the temperature differences $T_s - T_f$, as well as $h_c$, are not constant over a certain surface area. For instance, in the case of a hot vertically-oriented plate, the temperature of the fluid rises with the flow of air from bottom to top. The temperature difference can be specified for different values of $T_f$, including linear mean temperature differences, logarithmic mean temperature differences, inlet temperatures and adiabatic temperatures. In this thesis, the inlet temperature is used for convenience, however, for detailed approximations, it is advised that the logarithmic mean temperature be used [66].

The heat transfer coefficient can be related to the Nusselt number, $Nu$, which is one of many dimensionless numbers that is used in fluid dynamics to describe the behavior of fluids. $h_c$ and $Nu$ can be applied in different ways. Depending on the type of geometry used, they are defined based on different lengths. Specifically, $Nu$ is defined by many different correlations that are dependent on the type of geometry used and can be found in...
2.3. GENERAL HEAT TRANSFER THEORY

heat transfer handbooks. *Nu* for a surface with a specific dimension *Lc* can be described through the following equation:

\[
Nu = \frac{h_c \cdot L_c}{k_f} \iff h_c = \frac{k_f \cdot NuL}{L_c}
\] (2.3.4)

To obtain the Nusselt number, approaches are described in the many existing handbooks on heat transfer. Therefore, a detailed discussion will be foregone in this thesis. If it becomes necessary to obtain general information, a review of heat transfer handbooks is recommended. More information about accuracy issues for applying heat transfer correlations in practice is described by Lasance in his paper on heat transfer correlations applied to electronic cooling [43].

2.3.3 Radiation

Radiation is the transfer of heat between two bodies by means of electromagnetic waves [54]. Here, a general formula for calculating radiation between two bodies is presented. The equation is used to quickly approximate radiation heat transfer and is applicable when the surface area of the radiating body is significantly smaller than the surface area of the absorbing body (\(A_1 \ll A_2\)). In radiation heat transfer, heat flow \(q\) is a function of the Stefan-Boltzmann constant \(\sigma\), the emissivity between two bodies \(\epsilon\), the view factor between the bodies \(F_{1,2}\), the surface area of the radiating body (hotspot) \(A\) and the temperatures of the radiating and absorbing two surfaces \(T_1\) and \(T_2\), respectively. The equation describing this is as follows:

\[
q = \epsilon \sigma F_{1,2} A(T_1^4 - T_2^4)
\] (2.3.5)

In order to practically apply radiation in RC-networks, it is convenient to derive the heat transfer coefficient for radiation \(h_r\), as follows:

\[
h_r = \epsilon \sigma F_{1,2}(T_1^2 + T_2^2)(T_1 + T_2)
\] (2.3.6)

Provided that \(T_1 \approx T_2 \approx T_{av}\), an approximation in a more simplified form can be derived as follows:

\[
h_r \approx \epsilon \sigma F_{1,2} 4T_{av}^3
\] (2.3.7)

2.3.4 Thermal resistor/capacitor networks

As described earlier in this thesis, heat transfer in an electronic product can be modeled in the same way as electrical circuits by means of thermal RC-networks. In thermal RC-networks, an analogy of voltage difference \(V\) is temperature difference \(\Delta T\), resistance \(R\) is thermal resistance \(\theta\), current \(I\) is heat flow \(q\) and electrical capacity \(C\) is heat capacity \(C\). Inertia in the thermal domain does not exist [38]. Based on this, the following equations can be determined:
CHAPTER 2. THERMAL DESIGN, THEORY AND TOOLS

General equation:

\[ \Delta T = \theta \cdot q \iff V = R \cdot I \]  
(2.3.8)

Conductive thermal resistance:

\[ \theta_k = \frac{x}{k \cdot A} \]  
(2.3.9)

Convective thermal resistance:

\[ \theta_c = \frac{1}{h_c \cdot A} \]  
(2.3.10)

Radiative thermal resistance:

\[ \theta_r = \frac{1}{h_r \cdot A} \]  
(2.3.11)

Thermal capacitance:

\[ C = m \cdot c_p \]  
(2.3.12)

Time-constant in transient behavior:

\[ X = \theta \cdot C \]  
(2.3.13)

2.3.5 Compact thermal models

Compact models are used to characterize the thermal aspects of a component by means of a resistor network or resistor capacitor network. The models can be used to approximate the junction temperatures in a semi-conductor, such as a transistor.

Although complex models exist, until now, only simple models have reached wide applications and standardization, such as the two-resistor JEDEC (Joint Electronic Device Engineering Council) model. The accuracy of these two-resistor models is not very good. Therefore, more complex models, such as the Delphi model, have been proposed [65, 57]. Although such complex models are far more accurate, their adoption in the industry has not been widely accepted.

2.4 Analysis and simulation

During the design process of an electronic product, the design choices for the concept or detailed levels can be evaluated by analysing heat transfer on a theoretical basis and simulation on a numerical basis. With regards to analysis, heat transfer correlations, RC-networks and FNM are used. Such techniques are generally applied during the conceptual design phase and can be calculated by using spread sheets. For simulation, CFD and FEA software packages are available. Although these techniques are generally applied
during the detailed design phase, some applications in conceptual design have also been developed. In this section, we will further elaborate on these issues and present some developments found in literature on this subject.

2.4.1 Correlations and spreadsheet models - concept phase

The most important and difficult issue for thermal analysis during the conceptual design phase is the ability to obtain reliable heat transfer coefficients. Usually, handbooks on heat transfer describe the Nusselt number correlations for various types of situations. Accordingly, thermal design specialists usually create their own spreadsheets to evaluate these correlations.

In addition to the general theory found in handbooks, several publications on concept phase design exist in the field of thermal management. One example is an article by Teertstra et al., titled “Modeling of natural convection in electronic enclosures” [63]. In this article, the authors describe an analytical model that calculates natural convection in an electronic enclosure. Correct values for natural convection are usually more difficult to obtain than forced convection. The authors focus on the conceptual design phase of electronic products. The described model encompasses the positioning of a heat source (plate) within an enclosure. The result is a model that can be used to define the Nusselt number, which is needed to determine the convection heat transfer coefficient. The model encompasses two asymptotes. One defines the minimal spacing between an enclosure and a heat source, where conduction is the main source of heat transfer. The other demonstrates where enough space is available between the heat source and the enclosure for natural convection to take place. However, this model does not take into account radiation. Other research has shown this to be of major significance in the thermal analysis of naturally cooled enclosures [11]. Nevertheless, the model described in this article is very practical for finding heat transfer coefficients in natural convection.

Another approach to finding boundary conditions is described by Izhizuka and Hayama in their paper, “Application of a semi-empirical approach to thermal design of electronic equipment” [31]. The authors state that a semi-empirical method for calculating heat transfer in electronic devices results in an analytical model that supports the extraction of boundary conditions for use as input for numerical computer simulation. The method can be described as follows: on the basis of design input parameters, a flow pattern is calculated using a simple CFD model. This flow pattern is used to draw the flow paths. From these flow paths, the heat transfer coefficient for different nodes is calculated using pressure drops, volume flows and rate changes of entropy. The heat transfer coefficient is then used to calculate temperatures within the system. This paper also includes an example of the method applied to a case study. The approach described is depicted in figure 2.4.

With regards to conceptual design, an interesting approach for front-end analysis is described by Malhammar in his book “Thermal design for electronics” [44]. The author describes the concepts of cooling and board and air efficiencies. These methods require a certain amount of field data from existing products. Although such data is often hard to obtain, the resulting insight in the efficiency of new designs can be of high value for a
Designing electronic equipment
1. Casing configuration
2. PCB arrangement
3. Heat dissipation distribution
4. Designed temperature, $T_d$
5. Total flow rate
6. Fan selection

- Take flow path as heat flow path
- Solve equations for Air temperature, $T$
- Obtain surface temperature, $T_s$ for equipment
- If $|T_s - T_d| < \varepsilon$
  - Display temperature field
- Obtain flow pattern using flow visualization
- Divide flow lines with nodal points and form flow paths
- Give flow resistance coeff., $K$ and cross section area, $A$ for each flow path
- Solve nonlinear equations for flow rate, $V$ and pressure, $P$
- Obtain velocity, $u$ for each flow path from $u = V/A$
- Calculate, $Re$ number
- Evaluate heat transfer coeff., $\alpha$

Figure 2.4: flow chart for a semi-empirical design of electronic equipment [31]

company and a good basis for a front-end analysis of concepts.

An analysis of passively cooled electronics is usually more difficult to complete than actively cooled electronics because natural convection is very difficult to predict. An interesting method for approaching the design of such naturally cooled electronics is described by Newberger. His paper, “Totally enclosed naturally cooled electronic enclosures”, describes a methodology that can be used to analyze temperatures in sealed enclosures [47]. The goal of this methodology is to analyze preliminary design trade-offs and thermal design feasibility against a detailed software analysis, such as computational fluid dynamics and a finite element analysis. This method should be used during the early phases of a design of high-power density-enclosed devices. The author also states that the average internal temperature is a bad characterization because temperature gradients in such a device can be large. In the following, the theory forming the background for this model is given and several important parameters evaluating the preliminary design are described:

1. Flow areal power density.
2. Surface areal power density.
3. Draft height.
4. The overall heat transfer coefficient.
2.4. ANALYSIS AND SIMULATION

A range of combined radiative/convective internal and external heat transfer coefficients are described and guidelines for developing sealed encasings are given below:

1. Achieve uniform power dissipation on a printed circuit board (PCB).
2. Use screens inside to accurately direct the airflow.
3. Increase emissivity of the external surface.
4. Attach heat sources to the encasing.
5. Vertically orient PCBs.
6. Provide sufficient return-duct area.
7. Vent plastic enclosures.

2.4.2 Flow network modeling - end of conceptual design phase

At the end of the conceptual design phase and at the beginning of the detail design flow network modeling (FNM), a good technique is used to evaluate one or more structural concepts. The approach of FNM is comparable to resistor network models, but instead of using heat transfer resistance, the method uses airflow resistance to calculate the variations of airflow in a device. FNM is most appropriate for forced convection applications. In passively cooled systems, it is usually very difficult to predict the passive airflow through a device and the significant effects of radiation on heat transfer in a device. Belady et al.’s paper, titled “Improving productivity in electronic packaging with flow network modeling (FNM)”, describes an application of FNM for an electronic product in the conceptual design phase [3].

2.4.3 Computational fluid dynamics - the detail design phase

With computational fluid dynamics (CFD), complex fluid phenomena are simulated by means of numerical models. CFD has earned an important role in both thermal design practices and the thermal design research community. CFD is generally seen as a method most appropriate for the detail design phase. However, CFD may be applied during the preliminary stages of a design when combined with flow network modeling. For instance, it can be used to find the flow distribution of an actively cooled system. Although boundary conditions derived through such an analysis do not provide reliable values for the estimated temperature of local hotspots, it can be used with reasonable accuracy to quickly evaluate structural designs.

An example of this model can be found in the paper titled “Thermal design of a desktop computer system using CFD analysis”, where authors Yu and Webb use a CFD program to improve the cooling of a desktop computer [72]. The authors state that CFD can be used to quickly evaluate different desktop computer designs with reasonable accuracy. The authors then describe thermal resistance used in the analysis. In addition, the
differences between several heatsink options are taken into account. The authors finish
t heir discussion by outlining the effects of different cooling options.

CFD packages are generally not available in the design environment. The use of CFD
is regarded as an expert action and not something that the industrial designer could use
to generate structural concepts. In addition, CFD models, when applied to engineering
problems, will not give accurate temperature predictions, due to a lack of sufficiently
accurate input parameters and boundary conditions [41, 34].

2.4.4 Finite element analysis - the detail design phase

In finite element analysis (FEA), heat distribution is computed by a numerical analysis.
FEA already has widespread usage in both industry and research areas. For thermal de-
sign, finite element analysis is mostly appropriately used in densely packaged systems,
where conduction is the main mode of heat transfer. FEA can also be used for convect-
tive systems, although the approximation of boundary conditions (especially for natural
convection) is difficult to determine and must be obtained through CFD simulation or
experiments.

In practice, designers usually work with computer-aided design tools that support the
use of FEA packages. When a designer does not have such software, a thermal analysis
can be executed with the use of a spreadsheet program. An example of such an analysis
is shown in a study completed by de Jong et al. [15]. In this research project, an FEA
model was generated in Microsoft Excel and predicted, with reasonable accuracy, the
temperature distribution in a conventional power converter in the range of 20 watts.

2.5 Thermal design techniques

Although there are many different thermal design techniques used throughout system
and component levels (figure 2.5), only a brief overview of the most pertinent ones will
be given in this section. An evaluation of the application of the three most common
techniques, including fans, cooling fins and heat spreaders, such as heat pipes, is given by
Shulers in his article, “Thermal management: Understanding how to incorporate effective
thermal strategies into overall portable electronic design for better performance” [58].
The author describes both the analysis of a study on thermal strategies and temperature
distributions in several portable computers. The conclusion is that the main focus for
notebook cooling is on the central processing unit (CPU). The use of passive cooling
devices, such as cooling fins and heat pipes, in combination with a fan, results in the best
temperature maintenance. In practice, there is a wide range of differences for cooling
efficiency between products (in this case notebooks) developed by different companies.
A good thermal design can be a competitive advantage from a performance point-of-view.
2.5. THERMAL DESIGN TECHNIQUES

2.5.1 Cooling fins

Cooling fins are used to increase the surface area through which heat is dissipated and therefore result in lower thermal resistance from component surface to the ambient/fluid environment. An important aspect to remember when using a cooling fin is proper attachment to the hotspot to reduce interface resistance. Usually, conductive paste is used. Manufacturers of cooling fins determine thermal resistance of the component so that $\Delta T$ can be approximated. For proper application of cooling fins, it is advised to review the literature on the subject or contact a manufacturer.

2.5.2 Fans - forced convection

A fan is a device that blows or draws air through a product. The result of forced airflow through an electronic product is that the heat transfer coefficient increases and temperature decreases. Heat transfer rates can be approximately ten times higher than natural convection systems [61]. Although forced convection significantly improves heat transfer when compared to natural convection, the effect is limited. Usually, airflow of around 2 m/s is the maximum attained amount in practical applications [44]. Higher airflows would require the manufacturer to include earplugs with the product, due to a significant increase in noise.

In order to correctly apply fans in a design, understanding the principles of flow dynamics, such as pressure drop, dynamic pressure, static pressure and flow resistance, is important. In addition, an understanding of the flow impedance of a fan curve is needed.

2.5.3 Heat pipes

Heat pipes are devices that transport power from a hotspot (the evaporator side) towards a location where the heat can be conveniently dissipated out into the environment (condenser), usually through a heat exchanger, in combination with a fan. Inside the heat pipe, a fluid vaporizes at the location of the hotspot. The vapor is then transported from the center to the condenser side, where it is condensed. The condensed liquid is then transported back to the hotspot by capillary motion, through a wick on the inside surface of the tube. Heat pipes are convenient to use when components are situated in an
inconvenient location.

2.5.4 Thermoelectric coolers

Thermoelectric coolers, or Peltier-elements, can be used to transfer heat by means of applying direct current through two different metals, causing a temperature difference. Thermoelectric coolers are generally used in applications that require temperature stabilization, temperature cycling, or cooling below ambience [21].

2.5.5 Micro-channel heat exchangers

Micro-channel heat exchangers function similarly to cooling fins. They remove heat from a processor, to which they are attached, and manage high heat fluctuations. Combined with water as a cooling medium, micro-channel heat exchangers can deal with high heat fluctuations in processors. This technique is often seen in gaming computers. Micro-channel heat exchangers are costly, due to resources needed to develop machining and the pumping system. Although new manufacturing technologies help reduce costs, it will still take some time before widespread commercial application is a reality [67].

2.5.6 Embedded electronic components

One approach to the development of portable and wearable electronics with high power density is embedding components in a particular material. The article “Thermal management strategies for embedded electronic components of wearable computers”, by Egan and Amon, describes the effect of embedding an electronic artifact into a polyurethane substrate for heat transfer in small electronic devices [18]. Embedding an electronic component has two significant effects:

1. It adds a conductive medium, resulting in a reduced component temperature (increased reliability).
2. It adds a protective encasing (increased ruggedness).

The research described here shows the effects of several embedded electronic artifact configurations on the temperature rise of electronic components. The authors use CFD and resistor networks and experiments to analyze the effects of the different configurations on component temperature.

2.5.7 Structural concept optimization

In densely packed structures, such as power converters, integration technologies can be used to improve the structural concept. By using integration technologies, the design of an electronic AC-DC converter can result in higher power density and reduced average printed circuit board (pcb) temperature. In their paper “Improving the thermal management of AC-DC converters using integration technologies” [14], deJong et. al discuss
2.5. THERMAL DESIGN TECHNIQUES

how integration technologies on a PCB can improve the power density and thermal performance of a 20 watt AC-DC converter.

De Jong gives an overview of the integration technologies described in literature, including geometrical, electromagnetic and thermal integration. Geometrical integration entails placing components as close together as possible. The use of flexible PCBs can improve this form of integration in small electronic packages. Electromagnetic integration encompasses the integration of electromagnetic functions within the PCB layers. Examples include inductive (printing coils on the PCB), resistive, capacitive and thermal functions (such as extra copper layers for optimal conduction through the PCB). The third type of integration, thermal integration, involves placing high temperature and low temperature components close together in such a manner that components are most able to reach their optimal individual temperature. Flexible PCBs can help improve this type of integration. The author follows this discussion by describing a case study in which a 20 Watt AC-DC converter circuit is developed using three different methods: conventional, a combination of rigid and flexible PCBs and flexible PCBs only. Designs are evaluated using a finite difference method and are based on temperature measurements.

Another area worth mentioning is the placement of components on a PCB. In “Multi-objective optimal placement of convectively and conductively cooled electronic components on printed wiring boards”, Queipo and Gil describe how a combination of Pareto optimization, with multi-attribute utility analysis (MAUA), can be used to determine the best component placement [53]. Several design objectives, such as failure rates and total wire length, are integrated into one solution methodology, which is described by using the following:

1. “A heat transfer solver” for temperature prediction.
2. “A multi-objective optimization strategy”.
3. “A genetic algorithm” to find the most optimal solution.

Another approach in optimization is described by Eliasi et al. in their paper titled “Monte Carlo thermal optimisation of populated printed circuit board” [19]. The authors describe a method that will improve the placement of components on printed circuit boards with regards to reliability. The method consists of two stages. First, finite element analysis is used to calculate temperature distribution for an initial board layout. Second, the placement of components is optimized by using Monte Carlo annealing and cluster techniques. The result of this procedure is a reduction in computation time. The authors show that using heuristic stochastic optimization methods during the design of electronic systems can reduce development time.

In their article “Component-placement optimization for convectively cooled electronics”, Dancer and Pecht discuss the optimization of electronic device positioning by comparing several solution techniques, including enumeration, rule of thumb, dynamic programming, linear priority indexing, partitioning by quadratic approximation and partitioning by empirical equation [13]. This article mostly focuses on comparing solution techniques, determining accuracy and computation time. The techniques are applied to
a set of three problems. From the results, it can be concluded that the linear priority indexing method results in a significant reduction in computational time with relatively good accuracy. However, it is only useful for determining weak nonlinear problems.

### 2.5.8 Power management

In microprocessor-based portable products, power management is used to minimise energy consumption during product use. Power management includes employing a range of techniques that minimize power consumption of electronic products, such as slowing or shutting down components. Power management has a great deal of potential in developing energy-efficient products. Successful research has been executed and extensively discussed in power management literature.

Research in the area of power management, especially in the case of general purpose microprocessors, focuses on mechanisms, policies and architecture [52]. Policies determine the management of a component on the basis of utility curves, which describe performance or quality with regards to power consumption or other costs. The mechanism has the intelligence to actually control the component. A reduction in energy consumption of components is realized by improving the use of mechanisms, such as exploiting sleep modes, voltage/frequency scaling and battery recovery.

Two main sources of energy drain in the majority of microelectronic-based portable electronic products have been identified [22]. Energy consumption is first caused by an internal and external transfer of information. Second, computation energy is consumed by processing tasks. During optimal product design, both of these problems need to be discussed. In the case of portable electronic products, communication will increasingly contribute to power consumption. The main principles increasing efficiency in communication prevent unsuccessful tasks and minimize the amount of communicated information [23]. According to the literature, energy consumption can be reduced by determining high layers of a microelectronic system, systems architecture, operating system, and the entire communication networks and also by taking into account aspects of use, such as contextual relations and user intention [22, 52]. The key to designing energy-efficient portable products is to take energy efficiency into account at all levels of product design. In addition, most important energy consumption improvements can be implemented on higher levels of a system. However, at higher levels, calculating energy consumption is less comprehensive. Important in the development of power management techniques is the installation of power-efficient components. Developers mainly focus on interfaces, information storage, efficient processors and power sources, including batteries.

Current literature describes many theories on managing the power in electronic products. However, it is limited by two issues. First, no significant study was found that discussed the use of contextual relations, functionality or applying profiles to the design of energy-efficient products. Although the authors of this study did find some minor attempted studies in this area [12, 48], no major study was found. In order to optimize the energy efficiency of portable devices, the use of contextual relations, such as use profiles, is needed to optimally control power management activities. Second, the effects from applying power management mechanisms based on the dynamic behavior of power sources
2.5. THERMAL DESIGN TECHNIQUES

has not been extensively studied. Although some papers were found discussing the improvement of batteries [10, 4, 5], no significant research on the use of alternative power sources in relation to power management was found. An explanation for this is that alternative power sources are currently not appropriate for use in commercially portable products, due to a lack of knowledge and research.

2.5.9 Thermal management

Thermal management is an issue that is applied when a design is ready and must be improved for optimal reliability during use. Thermal management can be described as a series of hardware and software approaches that work dynamically in order to manage the operating temperature of components and modules. Thermal management is needed to maintain system reliability and reduce cooling costs by giving economical software or hardware reactions to reduce power, while minimally influencing performance. Because maximum allowable operating temperatures only occur at peak periods of operation, dynamic thermal management focuses on reducing workload and energy dissipation when the workload operates above the maximum power point for a prolonged period of time [9].

Thermal and power management are two issues frequently discussed in literature discussing portable electronics. There has been research on a dynamic management framework that combines both temperature and power management. Temperature management is necessary to gain reliability, while power management is applied to increase battery lifetime. Although these issues are closely linked, a dynamic framework for this idea has only recently been described in literature [25]. Huang et al. describe a Dynamic Energy Efficiency and Temperature Management (DEETM) framework that manages both power and temperature management techniques. In this article, a framework is described that attempts to fulfill two goals, namely, optimizing energy efficiency and reducing temperature. The framework uses two algorithms, one which implements energy efficiency and one for temperature control.

In their article “An Overview of Thermal Management for Next Generation Micro-electronic Devices” [64], Tonapi et. al describe thermal management issues in complex-high-end systems, consumer electronics, military electronics, aerospace electronics and the role of thermal interface materials. The authors describe portable electronic product components that do not dissipate high power due to restrictions in the low energy density of batteries. Therefore, heat dissipation is mainly an issue with regards to the reliability of device junctions. The goal of thermal cooling in such products is to minimize thermal resistance between the junction and case by attaching a heat sink to high-dissipating components using some sort of thermal interface material. In order to maintain a reliable junction temperature, cooling aspects of thermal interface material become very important because when generated heat is inefficiently transported to the heat sink, high-junction temperatures cause systems to be unreliable. Therefore, thermal interface materials need to be improved so they can cope with future conductivity needs.

In the article “Thermal characterization of compact electronic systems: A portable PC as a study case”, Dallago and Venchi evaluate the aspects of radiation, material use
and operating conditions on the thermal behavior of products with high-power density [11]. According to the authors, most microelectronic systems used in portable electronic devices rely on conduction, natural convection and radiation. Conduction and convection are significant to almost every electronic system. However, because radiation is comparable to convection in passively cooled systems, the accuracy of numerical thermal modeling depends on the handling of radiation. In compact electronic systems, natural convection is hindered by tightly packaged boards and devices. Previous research shows that taking into account radiation significantly improves the accuracy of numerical simulation.

The unfamiliarity of thermal aspects by designers is also an issue facing some studies. In their paper “Internet-based instruction for thermal design of electronic products - making a global impact” [35], Joshi et al describe their efforts to develop a multi-institutional web-based thermal design course. The authors describe the modules used in the course. In addition, a case study on a video conference network developed by the authors is evaluated. The website contains a great deal of pertinent information about heat transfer.

2.6 Electronics reliability

Electronics reliability is an issue that is mostly related to the thermal design of electronic products. In his paper “Thermally driven reliability issues in microelectronic systems: status-quo and challenges,” Lasance discusses some significant issues in thermal and reliability engineering of electronic systems [42]. The author states that without changes in the development process of the microelectronics industry, a successfully implemented commercial application using nano- or micro-electronics technology will not take place. Lasance describes reasons that obstruct the commercial success of micro- and nano-technology. The most important problem is that current tools and theories cannot cope with reliability issues, due to changing physical and mechanical properties. Furthermore, the author proposes a combined responsibility between components and systems manufacturers. Eventually, the implementation of state-of-the-art expertise at the beginning of the design process will lead to products that are more reliable, cheaper, smaller and that reach the market earlier.

Traditional reliability prediction methods are mainly derived from the MIL-HDBK-217, which is a military reliability prediction handbook [17]. The main problems associated with this method are using outdated data that outlines questionable validity for the models used, focusing on failed components or subsystems instead of field failure, having reliability better related to system design than component design, having component failure caused from issues other than component-related causes and having outdated modeling for failure rates. Pech’s 1996 article “Why the traditional reliability prediction models do not work - is there an alternative?” [51] describes problems with traditional reliability prediction methods and proposes an alternative approach—physics-of-failure, which improves electronic system reliability and focuses on the fundamental mechanical, electrical, thermal and chemical processes and on identifying and solving potential
2.7 LITERATURE RELEVANT TO CONCEPTUAL DESIGN

<table>
<thead>
<tr>
<th>Publication</th>
<th>Method</th>
<th>Configuration</th>
</tr>
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<td>Ishizuka, 1986 [32]</td>
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<td>open encasing passive cooling</td>
</tr>
<tr>
<td></td>
<td>2) measurements</td>
<td></td>
</tr>
<tr>
<td>Newberger, 1996 [47]</td>
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<td>closed encasing passive cooling</td>
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<tr>
<td></td>
<td>2) measurements</td>
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<tr>
<td>Belady, 1999 [3]</td>
<td>1) correlations/spreadsheets</td>
<td>open encasing active cooling</td>
</tr>
<tr>
<td></td>
<td>2) flow network model</td>
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<td></td>
<td>3) computational fluid dynamics</td>
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<td></td>
<td>4) measurements</td>
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<tr>
<td>Ishizuka, 2000 [31]</td>
<td>see figure 2.4</td>
<td>open encasing active cooling</td>
</tr>
<tr>
<td>Yu, 2001 [72]</td>
<td>1) defining max th. res. $\theta_{tot}$</td>
<td>open encasing active cooling</td>
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<td></td>
<td>2) computational fluid dynamics analysis</td>
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<td>Yazawa, 2002 [70]</td>
<td>1) black box analysis</td>
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<td></td>
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<td></td>
<td>2) computational fluid dynamics</td>
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</tbody>
</table>

Table 2.1: Literature related to conceptual thermal design.

problems before they occur. A goal of physics-of-failure-based processes is that weaknesses can be identified during the design process and reliable physical designs can be developed before beginning the process of accelerated lifecycle testing.

In Parry et al.’s article “Enhanced Electronic System Reliability - Challenges for Temperature Prediction”, the authors evaluate goals for electronic system reliability with regards to temperature prediction [50]. This issue is becoming more important because of the increase in telecommunication in society. This developing industry causes high competition among companies and places a high level of dependence on system reliability. Parry et al.’s paper begins by pointing out the fact that often, prediction accuracy is low because of a gap in knowledge between temperature analysis and system lifetime assessment. The authors point out the difference between electronic systems that depend on processors and those that do not and conclude that the standards often used in reliability testing do not make sense.

2.7 Literature relevant to conceptual design

From the literature study, several papers have been selected that focus on the conceptual thermal design of electronic products. References to these papers are given in table 2.1. Although the importance of thermal design during the conceptual phase is discussed in all of these papers, only two papers actually propose a methodological improvement [31, 3]. Both Ishizuka and Belady focus on an open encasing with active cooling (forced convection) and use flow network modeling (FNM). The methodological description of
Belady focuses on the positioning and integration of FNM in the design process (figure 2.3). Ishizuka, on the other hand, comprehensively describes a flow chart for the calculation procedure. Although both publications focus on thermal design methodology in preliminary design phases, an important aspect of conceptual design, the definition of structural concepts, is not discussed in these two papers. Focus on a structural concept design is described in the paper “Totally enclosed naturally cooled electronic enclosures” [47]. In this paper, Newberger gives a set of guidelines that enhance the thermal design of electronic equipment, which can be used to optimize the thermal design of the structural concept phase for electronic products. Although the literature described here develops theories that can be applied to the conceptual phase of design, applying the theories during design is not evaluated. These studies focus instead on thermal design experts, rather than the common designer.

2.8 Conclusions

Thermal design can be summarized as the scope through which tools and methods control heat distribution within a product and dissipate this heat through an ambient environment. The aim of this study is to design products that have maximum performance and high reliability, fulfill international temperature safety standards and have good formgiving. Currently, the most comprehensive application of thermal design tools and methods is in the field of power-dense modules, such as power converters or DVD engines, and high-power density systems, such as laptop computers. In these fields, not only are thermal components considered, but power management as well. Eventually, the most competitive electronic products, from a thermal design point-of-view, will be those where the design team reaches optimal synergy between power management and thermal design.

In this chapter, the most common tools and techniques in the field of thermal design have been described. A brief introduction to thermal RC-networks has also been given. This method for modeling heat transfer in thermal design appears to be most appropriate for use in the conceptual phase of design. In addition, due to the increasing power density of electronic products, designers must focus more on thermal design throughout the design process. The (common)industrial designer will therefore become increasingly involved in thermal design. It is the author’s opinion that the current literature available on thermal design mainly focuses on thermal design specialists. This creates a gap between available knowledge and the industrial designer. A new focus on the area of thermal design is needed to close this gap and bring about an application of existing thermal design tools and techniques for the industrial designer.

This thesis deals with design-based research, focusing on finding new approaches that can improve the performance of the industrial designer. It is with this viewpoint in mind that the tools and methods available and presented in this chapter will be compared to tools and methods currently used by industrial designers in their day-to-day practices. It is believed that such an approach will reveal the main problems in the field and will provide direction toward improvement.
Thermal design in practice

In this chapter, thermal design will be discussed from a practical point of view. Using interviews obtained from designers from the field, an overview is given for the tools and methods applied by designers and directions suggested for improving thermal design during the conceptual phase. Based on these interviews, three directions are proposed for improving the thermal design process.
CHAPTER 3. THERMAL DESIGN IN PRACTICE

3.1 Introduction

In the previous chapter, the tools and methods described in literature were discussed. Literary research shows that there are abundant tools and methods available for executing a thermal analysis for electronic products during different phases in the design process. Examples include the following:

- Spreadsheet calculations
- Resistor capacitor networks
- Flow resistance networks
- The finite element/difference method
- Computational fluid dynamics

Although the applicability and accuracy of these tools and methods has been proven, it still remains unclear how they are applied during the design process. Especially for industrial design engineers, the need for tools to be used during the conceptual design of electronic equipment is significant. It is during this phase of the product development process that important design choices are made that influence developmental lead time, costs and technical feasibility.

The expectations set in the previous chapter include tools and methods described in literature that are mostly applied during the detail design phase. There is a gap between the thermal design theory described in literature and the application of the thermal design theory in practice. Interviews with designers in the field are used to discuss the question *What are the main problems from a practical point of view?* Based on the results, directions for developing models and methods will be proposed. The resulting directions determined from the interviews are a basis for the further development of three thermal design models and methods, described in chapters 4, 5 and 6.

3.2 Approach

The method that has been used for this study is based on in-depth interviews. This method has been chosen because of the explorative nature of this particular research project. In-depth interviews give opportunities for obtaining large amounts of information from a relatively small set of participants who have sufficient, heterogenic backgrounds. The structure of the interviews encompasses four topics and are defined as follows:

1. The variety of development processes.
2. The practice of thermal design.
3. Main problems from a practical point of view.
4. The need for easy-to-use formulas.

Participants were selected using an iterative manner, focusing on their heterogeneity between job function, educational background and experience. Participants were selected and contacted based on “snowballing” through contacts. First, colleagues from the faculty of design engineering in Delft, who are involved in the design of electronic products, were interviewed. After the first interviews were conducted, a new selection of participants was proposed by asking the first participants to suggest an acquaintance with similar experience in thermal design. The approach resulted in a group of seventeen participants, who are designers with heterogenic backgrounds, job functions and experiences.

<table>
<thead>
<tr>
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<td>face-to-face</td>
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</table>

Table 3.1: Participants from preliminary interviews.

As an introduction, questions focused on the type of electronic products in which the participant is involved and what level of knowledge they employed on the subject of thermal design. The interview proceeded by asking the participants to provide a description of the design process. The idea is to compare results from the discussion section with ideas centered around the general design process (figure 3.1) often used in industrial designs [56].

The interview then focused on thermal design aspects of electronic products. Issues that arise during the design process, such as hotspots, the ergonomics of the encasing temperature and temperature criteria with regards to components, were discussed. Options used to solve thermal problems were also discussed, including the placement of
components, forced or natural convection, conduction of heat to the encasing and the use of heat pipes, cooling fins and Peltier elements.

The interview then focused on the decision process of thermal design. The discussion involved design decisions, such as material choice and development costs. In addition, this section of the interview focused on the means available to the design engineer to support their decision process. The discussion involved available means, such as available handbooks, a manufacturer’s specifications, experience and the use of software tools.

During the next section of the interview, the participants were asked to explain a practical design project involving one or more thermal design problems. The focus of this part of the interview was exposing difficulties with some thermal designs. Results can be used to find gaps in knowledge between design theories and practice. The focus was aimed at conceptual design choices resulting in either an extra iteration in the design process, namely the occurrence of difficulties in the embodiment phase and detail phase, or product failure caused by incorrect conceptual design decisions.

Finally, participants were asked to give their opinion on the effects of improving thermal design using easy-to-use formulas. A proposition was laid for the participants involving optimizing the conceptual design phase by employing easy-to-use models that analyse temperature distribution in electronic products. Participants were given the explanation that the model should support conceptual design choices, such as form giving (volume and surface), material choice, active or passive cooling, placing components and PCBs in the encasing and applying cooling aids, such as cooling fins and heat pipes.

3.3 Results of the interviews

Results from the interviews will now be presented, based on topics described in the previous section, including a variety of development processes, thermal design practices, problems from a practical point of view and the need for easy-to-use formulas.

3.3.1 The variety of development processes

In this section, several design processes described by the participants will be explained (figure 3.2). The approaches described vary significantly from the general design process. In order to demonstrate this, the participants are divided into four categories:
3.3. RESULTS OF THE INTERVIEWS

Individual electronic designer. This category basically includes individuals who self-design the entire electronic prototype and choose the encasing from either a standard catalogue or make a mock-up to test thermal design.

Power converter designer. In the present case, several people involved in power converter research were interviewed. This type of designer works by means of an iterative process and completes both electronic and mechanical designs, but mainly focuses on electronic design. Here, energy efficiency, electromagnetic compatibility (EMC) and thermal design work hand-in-hand and are the specific drivers in the process.

Thermal expert. Thermal experts work with the input given by the design team and develop several thermal concepts within the basic design constraint. This type of designer must often deal with a lack of thermal design knowledge on the part of the industrial designer.

Industrial design engineer. These individuals work using a concurrent engineering development process, where the mechanical, hardware and software designs are simultaneously developed. One of the problems with this area is that the power dissipated by components is unclear during early phases of mechanical design.

In general, participants describe the design process as an iterative process. Each type of engineer has specific steps during iteration. Power converter researchers describe their process as involving circuit, thermal and EMC design (figure 3.2). From designing the electrical circuit to evaluating requirements with regards to thermal concepts, their process usually begins with resistor network calculations and then a finite element analysis. CFD is not mentioned and probably not used because convection is not the main heat transfer mechanism for these type of designs.

The industrial design engineer also regards the process as iterative; when design changes occur, the product is re-tested. Participant 14 specifically described the following steps during thermal design:

1. **Criteria/specifications with regards to maximum allowed temperatures of (critical) components**

2. **Power analysis/location of hotspots/critical components**

3. **Measurements**
   - Identifying cooling options
   - Testing
   - Changing concepts

4. In a detailed analysis, thermal problems are prevented using thermal management algorithms that define “graceful degradation” (shut down of components).
Industrial design engineers explain that the throughput time of developing a new product platform is two years. During the design process, the focus is first on the function of the product and then on thermal design. During the project, all disciplines and items of hardware, software and design are concurrently developed.

Thermal design specialists view the design process differently. This type of designer usually receives a problem based on a design concept. Throughout the development of these types of devices, an electronic and mechanical design is proposed. There are some cooling concepts with the mechanical design. In principle, the mechanical design is developed and then given to the thermal designer, who aims at assessing several cooling concepts within design constraints.

The following cooling concepts are very important and include height, passive and active cooling and the placement of modules. Participant 17, a thermal design expert, explains, “On a conceptual level, the designer focuses on a quick answer; because you are talking about concepts, you do not want to have too much detail. The goal is to do a concept study as quick as possible in a standardized way. Often, I do a pre-study in software and then build the hardware to verify the software model. Hardware usually means that you need facilities, which results in large overhead costs”.

Figure 3.2: Design processes from interviews.
3.3. RESULTS OF THE INTERVIEWS

The projects in which Participant 17 is involved have a throughput time of three to six months. Because a designer must do everything within a small time period, the design is usually an extension of a product already developed. Participant 17 further explains, “The current approach will therefore never lead to a revolutionary design if you have not looked ahead from a conceptual point of view. The design has boundary conditions because of the existence of standard modules”. Participant 17 suggests the importance of focusing on improving the thermal design relationship between design concepts and module design in order to improve the innovation of a design.

3.3.2 The practice of thermal design

This section describes how participants currently deal with thermal design. Thermal design aspects will be described on the basis of several important elements present in the development process. This study first gives an overview of thermal design requirements. Then, the authors follow with a description of the design of a structural concept. The third section describes the means used for conducting a thermal analysis and simulation for a particular concept’s temperature behavior. The section finishes with a description of how measurements and prototypes are used during the design process.

Thermal design requirements

There are specific requirements for designing electronic equipment that focus on thermal design aspects. The following aspects have been derived from participant interviews:

- Maximum allowed temperature of components
- Size
- Ambient requirements
- Ergonomic requirements
- Cost

The maximum allowed temperature of components used in an electronic product is given in a manufacturer’s specifications. It is important for the designer to prevent components from reaching their maximum allowed temperature. If the components exceed this temperature, the reliability of the component decreases. If a product fails because this level was ignored, the responsibility cannot be directed towards the component manufacturer. The offending company must then pay costs for repairs. For some components, the effects of temperature on life expectancy are also given and are used in analysing reliability. One participant remarked that “As long as we are within the maximum temperature range of the components, we are good. If we are above the maximum temperature range, then we have a problem because we cannot claim the manufacturer of the components”.

Design trends are aimed towards developing smaller and more compact products. This conflicts with thermal designs because a high-power density product is more difficult
to develop from a thermal design point of view than a product with low-power density. Some participants involved in the design of power converters specifically focus on this issue of increasing power density as much as possible in order to miniaturize the product. Concepts in this area are chosen on the basis of three requirements: 1) efficiency being more than 90%, 2) EMC compatibility and 3) preventing overheating. In this case, the function of a circuit must always make compromises for thermal and other requirements.

Requirements usually specify the ambient environment in which the product must be able to function. This brings about requirements, such as maximum ambient temperature in which the product must function, and dust and water requirements. Dust requirements make it difficult to cool the device and contradict efficient cooling. Participant 16 explains “With regards to dust and sound, you would like to make the device as closed as possible, but with regards to temperature, as open as possible”. For devices that are designed for harsh ambient environments, the thermal design becomes especially difficult to accomodate. In extreme situations, such as outdoor applications, where a lot of sand and high humidity is present, solutions are limited. In the case of dust requirements, sometimes filters can be used. The problem with filters, however, is that they must be replaced at a certain point in time.

Electro-magnetic compatibility (EMC) is also influenced by thermal design choices. EMC compatibility contradicts thermal design because when applying EMC, a designer wants the product to have a closed encasing and no turning magnets, which are used in fans. Holes in the encasing are generally not good for EMC shielding. According to Participant 16, “Often, it is a fight between how many holes you can put in a product and whether you can use a fan without causing EMC disturbance.”

Ergonomic requirements influence the thermal design of a product. With regards to encasing temperature and safety, specific regulations play a significant role. According to the International electrotechnical commission’s (IEC) regulations [27], for instance, the encasing temperature is not allowed to exceed 60°C. Participant 16 clarified by using the following example: “I can remember a router that I developed a few years ago. The encasing was ready and the heat dissipation was so much that the encasing had to be changed using many holes. At such a point, safety regulations, such as CEI IEC 60950, became an issue in design because the dimension of the holes was defined in the regulations”. Such requirements usually specify an appropriate level of noise level for a product. In this case, thermal design can also have its drawbacks if cooling is overemphasized. Participant 17 remarked, “You can have a perfectly cooled system but if there is much noise, then the customer will not buy the product.”

Another issue, reiterated by Participant 17, is that often, electronic designers tend to specify the maximum amount of power dissipated. However, this is not convenient, because power dissipation usually changes with employed use modes. In such a case, the cooling concept is over-dimensioned and costs are unnecessarily increased. Therefore, correct specifications for a variation in power dissipation in different usage scenarios is very important.

Participant 14 indicated several requirements needed for a sample product supposedly used in harsh environments table 3.2. In this case, dust requirements make it difficult to cool the device in the same way as, for example, a laptop. For this example,
3.3. RESULTS OF THE INTERVIEWS

<table>
<thead>
<tr>
<th>Thermal design criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand held: Encasing temperature is limited because the product must be hand-held.</td>
</tr>
<tr>
<td>IP 45: There cannot be airflow through the device.</td>
</tr>
<tr>
<td>Rugged: Thick encasing and double layers.</td>
</tr>
<tr>
<td>Compact: Limited dimensions; critical components are close together and the size of the heat sink is limited.</td>
</tr>
<tr>
<td>Portable: Different ways of positioning during use (no airflow in passive cooling).</td>
</tr>
<tr>
<td>Maximum temperature encasing: 55°C.</td>
</tr>
<tr>
<td>Maximum temperature Li-ion battery: 60°C.</td>
</tr>
<tr>
<td>Maximum temperature display: 70°C.</td>
</tr>
<tr>
<td>Maximum temperature electronic components: 85°C.</td>
</tr>
<tr>
<td>The environment temperature is 45°C to 50°C.</td>
</tr>
</tbody>
</table>

Table 3.2: Typical thermal design criteria of a described case.

passive cooling is preferred because of its robustness. Although active cooling is not preferred because of noise levels, reduced robustness, EMC disturbance and reduced life expectancy, a back-up function has been integrated into the design.

Thermal design

In this thesis, thermal design is defined as tools and techniques used to control the temperature of critical components in a design. Designers focus on several aspects of thermal design. In the case of passive cooling, focus is mostly placed on increasing a cooling surface area by means of cooling fins or the encasing. Thermal interface materials are used to reduce interface resistance between the component and increased surface area. If necessary, openings in the encasing may be added to improve the convection heat transfer coefficient inside the encasing. This, however, is not usually desirable because of dust requirements [26]. In the case of active cooling, a fan will be used.

Power management is directly related to power dissipation in components and can be applied during design. An example of efficient power management often used in circuits of power tools is pulse-width modulation (transistors). In integrated circuits, voltage-frequency scaling is often used. Table 3.3 shows an overview of the problem scope, versus the solutions scope, and will be described in the proceeding paragraphs.

Positioning/placement There is always a desired design concept for which engineers strive. Based on this desired design concept, the positioning of specific components, such as keyboards and displays, is fixed, although practical solutions are at times difficult to realize. Some components are functionally restricted to a certain position. Examples include the placement of buttons on a device or a transistor that must be attached to a heat sink. Electronics designers who develop single solutions or small series are frequently limited by the fact that a standard encasing is used where the placement of connectors is limited.

With regards to thermal design and component positioning, one power converter developer stated that normally, high-density heat components are positioned in the correct
### Problem scope

- Exceeding maximum allowed temperature.
- Decreasing life expectancy (reliability) of electronics.
- Reduction of quality (functionality) of the device.
  - shutting down product to cool down
  - reduced electromagnetic compatibility due to holes in encasing
  - reduced battery lifetime
  - reduced component lifetime
- Extra costs
- Variable ambient environment

### Solution scope

- Positioning and placement of components
- Heat spreading within the device
- Increased surface area through which heat dissipates into the environment
- Active cooling versus passive cooling
- Component choice
- Power management and thermal management

Table 3.3: Problem versus solution scope in thermal design of electronic systems.

... place before other components are placed. Although the placement of a fan and components on a PCB are variable during the initial phase of the design process, in the conceptual phase, it is difficult to evaluate the placement of components because the dissipation per component is often unclear. Participant 5 responded, “It would be good if designers had some guidelines on product size, placement of openings and the amount of air needed. A relationship between the size of a product and the power that is dissipated would be a good start.”

### Conducting and spreading heat

Dissipated heat in an electronic product must be controlled to keep the design within certain specifications. In order to do this, heat must be conducted away from the hotspot to a location where it can be optimally transferred to an ambient environment. This is done by increasing the surface area (passive cooling), by using a fan (active cooling) or a combination of both.

There are several possible solutions for conducting heat within a product. Interface resistance on the surface of a component can be improved by using thermal interface materials, such as conductive paste. If there is little power dissipation in components, the heat can easily be conducted and spread into the copper layers of a PCB. Heat spreading can be optimized by means of extra vias in a PCB and by placing components with levels of high-loss density next to components with levels of low-loss density. If a component is positioned in a difficult location, a heat pipe can be used to transfer the heat to a area where more space would be available for a fan. In addition, it is necessary to discuss blocking heat flow from the direction of the source to the critical component and transporting it in the direction of an ambient environment as quickly as possible.

If heat transfer is properly controlled inside the product, heat can be transferred towards a location where the surface area can be increased. Possible solutions for extending...
surface area include the use of cooling fins, using a cooling plate, attaching components to the encasing or using extra copper layers on a printed circuit board. Conducting heat from a component to the encasing is difficult to incorporate in many electronic products. This is because important criteria exist with regards to the form of the encasing, the material used (plastic has a low thermal conductivity) and ergonomics (the encasing temperature is limited by safety regulations).

Encasing material is thus an important design choice. Participant 13 explains, “Material choice of the encasing is done during the conceptual design phase. We chose, for instance, to use magnesium because of its good properties on heat conduction and EMC shielding.”

Active/passive cooling Designers generally prefer passive cooling over active cooling. The main reason for this preference is that fans have certain drawbacks, including high levels of noise, high occurrences of after-sales repair, higher costs, more dust and moisture and electromagnetic interference. The choice between passive cooling and active cooling is generally not clearly described. This is reiterated through remarks from participants, including “If products become too small, then it will be necessary to use a fan. This, however, causes more noise. When noise is a problem, then natural cooling is the solution”, and “Passive cooling is possible by creating a chimney effect by making holes in the bottom and top of the device”. It appears that for some participants, qualitative motivation is based on experience and trial and error, not on basic heat transfer theory.

Component choice The choice of components influences the power dissipation within a product and thus also affects thermal design. Participant 4 suggested the following: “The choice of transistor is important; usually a transistor is chosen that can draw high currents and has few losses”. If specific components result in difficulties resolving problems, then it is necessary to look for alternatives to a particular design. Participant 16 remarked, “You can also look for alternatives in the design, for example, by replacing a lamp with an LED. So, as a designer, you must know how to use new technological solutions to prevent temperature problems in the design.”

Power management/thermal management In the design process, thermal design can be optimized by using power or thermal management. Power management is best for energy-efficient components and energy-efficient designs. This type of management should be discussed throughout all phases of the design process for optimal results [22]. Examples of energy efficient design include the pulse-width modulation of transistors, voltage frequency scaling in processors and integrated circuits. Power management in itself is an area of research; many studies are available on this topic. Participant 16 suggests, “The best solution is probably reducing heat dissipation, but this is something that the electronic engineer must do.”

When the electronic design is finished, thermal management can be used. If the product operates and reaches a critical situation, actions must be taken, such as reducing performance or initiating shutdown. In these situations, a thermal management algo-
rithm will often control the device and prevent critical situations. Participant 15 explains, *When the tests seemed reasonably optimal after several tests, we decided to apply a thermal management algorithm. This encompassed measuring temperature, processing the data and taking actions to prevent heat problems. This is what we call a safety net for temperature problems.*

**Thermal analysis and simulation**

According to participant interviews, thermal analysis in industrial design engineering appears to be restricted by several issues. Thermal analysis is often based on simulation by means of resistor networks, finite element analysis or CFD. Much of the required information necessary for calculation is gained through data sheets and experience. The novice designer constricts analysis by using simple hand calculations and manufacturer specifications. The experienced designer begins with spreadsheet models during the preliminary stages and later implements advanced techniques, such as thermal resistor/capacitor networks, computational fluid dynamics and finite element methods, during the more detailed stages.

When using theoretical approaches, such as resistor/capacitor networks, the reliability of predicting the values of thermal contact resistance, material properties and heat transfer coefficients is often very difficult to maintain. Usually, CFD and measurements are used to gain heat transfer coefficients. Participant 9, who works in the field of power converter research, indicated that *“One must be an expert in many physical phenomena to accurately predict the dissipated heat in components.”*

A mechanical designer with little thermal knowledge normally uses heat and thermal resistance to calculate steady-state temperature. For simple situations, back-of-the-envelope calculations are sufficient. However, most mechanical designers who were interviewed indicated that they do not often use theoretical models and instead look for practical solutions that result in lower costs. Participant 16 stated that it is very important for mechanical and electronic designers to develop an idea of what is possible. *“As a designer, you should have a tool that can discover the consistency of things.”*

Resistor/capacitor networks can be a powerful means for modeling thermal behavior. The result is a model that can be used in a thermal management algorithm to predict the behavior of a device beforehand. Participant 15 recalls, *“Once you have defined one global model of a product, then it is relatively easy to estimate successors of the unit.”* This points out the importance of resistor/capacitor networks for predicting the effects of design changes on temperature. When redesigning or upgrading an existing product platform, this can be an especially useful tool.

This section will now focus on the means that designers use to analyze temperatures in product concepts during practice. Table 3.4 shows topics that have been identified and that will be discussed.

**Transient calculations** During the interviews, the importance of transient analysis was discussed. As stated by Participant 2, a professor in industrial design engineering with a
3.3. RESULTS OF THE INTERVIEWS

<table>
<thead>
<tr>
<th>Thermal design topics</th>
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</thead>
<tbody>
<tr>
<td>Transient calculations</td>
</tr>
<tr>
<td>Manufacturer specifications</td>
</tr>
<tr>
<td>Software</td>
</tr>
<tr>
<td>- Spreadsheets</td>
</tr>
<tr>
<td>- CFD</td>
</tr>
<tr>
<td>- FEA</td>
</tr>
<tr>
<td>Convection heat transfer</td>
</tr>
<tr>
<td>Hiring an expert</td>
</tr>
<tr>
<td>Analysis process</td>
</tr>
<tr>
<td>Causes of heat dissipation</td>
</tr>
</tbody>
</table>

Table 3.4: Typical thermal design topics during development project.

solid background in product development, “It is important to look at the difference between energy and power. Thus, the relationship between the time during which a component with a specific heat capacity and maximum allowed temperature dissipates a certain amount of heat.” Participant 5 confirmed the same idea by stating, “Also important is the frequency in which a product is used in relation to the thermal capacity of critical components.”

Based on previous remarks, it is imperative to take transient analysis into account when designing models for future use.

**Manufacturer specifications** One issue emphasized during interviewing is that most of the participants heavily rely on specifications given by manufacturers. Participant 3 has been building university test equipment for many years and responded by stating, “My knowledge is limited to specifications and experience; I personally do not use thermal management handbooks”. In addition, Participant 4 said, “Mostly, the rule of thumb and manufacturers’ specifications are used as a guideline in analyzing thermal issues.”

The use of manufacturers specifications achieves several goals. First, they define thermal design criteria, such as the maximum allowed temperature of a component. Second, they define power dissipation in a component, which indicates where hotspots are located. Third, these specifications sometimes list the thermal resistance of a device (junction to case resistance for IC and thermal resistance for cooling fins). Such information can be used to approximate the temperature of hotspots.

A critical note on specifications is given by Participant 10, who states, “Manufacturers’ data sheets do not always give the right value”.

**Software, CFD, FEA** The subject of software will also be addressed. The aim here is to give an overview of how computational fluid dynamics and finite element analysis are used in design. Responses vary. Participant 3, for instance, merely mentions the existence of software: “There exist software packages that can calculate hotspots”. Others give a more specific description. Designers that work as single designers or in research do not involve software in thermal design activities. Developers from concurrent companies
usually outsource software analysis, such as CFD and FEA, to a specialized company. Sometimes, spreadsheet programs are used.

Although FEA software gives interesting results, respondents mainly regard results as an extra check of calculations and an addition to measurements on a mock-up or functional model. Participant 13 described the following: “We use finite element analysis to do thermal calculations. The difficulty is often that it gives nice pictures, which are of little value when you do not do manual calculations. Another drawback is that the computer models have to be simplified because too much detail would take too much time to model and calculate”. In addition, boundary conditions needed for FEA must be derived from measurements or CFD. In order to check the accuracy of the boundary conditions computed by the CFD model, measurements are used. Participant 15 explains, “We sometimes use finite element analysis, but boundary conditions that you must fill in are very diffuse. So, this means that you eventually have to go and measure again in order to tune boundary conditions in the finite element model to the measurements. At that point, you have already come so far that the use of such a finite element model is questionable. Finite elements can, however, be a good way to model heat transfer within a component (mainly, conduction plays a role). But, modeling complex air flow is virtually impossible.”

With regards to the use of CFD and FEA, Participant 17, a thermal design expert, describes his view in the following: “The main advantage of software is that you can see heat flows and you can design a system in such a way that the airflow goes through the device in a way that you like best. You also have the flexibility of calculating different variations. The advantage of hardware is that it is more accurate. You can also derive an RC-network from a CFD simulation. This allows you to make a model that shows where the main problems are and how to solve them. If you do not have hardware, then you depend on simulations. This is done with CFD software. The disadvantage is that complex shapes with moving components are difficult to simulate. With a resistor network, you do not calculate the heat transfer coefficients; a CFD package can do this, but if the grid is too rough, then the coefficients are unreliable, which results in an incorrect temperature estimation. Software is more flexible, but increasing accuracy increases time and decreases flexibility. Hardware is less flexible, but gives more accurate and reliable results”.

Finally, conversations with design experts show that spreadsheet software programs are used for first order analyses. This is in agreement with expectations specified in literature. Participant 17 describes, “We have a spreadsheet tool that tells us what the average temperature in a device is at a certain flow rate.”

Convection heat transfer It seems that only thermal management specialists discuss the possibilities of calculating convection heat transfer by hand. Participant 17 states, “You can also do hand calculations to estimate heat transfer coefficients. You can differentiate between free convection, where radiation plays a significant role, and forced convection, where it plays a less significant role. Even if you have holes in the encasing, most heat still leaves through the encasing. So, looking at the emissivity of the encasing
3.3. RESULTS OF THE INTERVIEWS

**Analysis and testing topics**

<table>
<thead>
<tr>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical models completed by a specialized company.</td>
</tr>
<tr>
<td>- Difficult and time-consuming.</td>
</tr>
<tr>
<td>- Based on assumptions.</td>
</tr>
<tr>
<td>- Impractical and too complex.</td>
</tr>
<tr>
<td>Infrared measurements given through a specialized company.</td>
</tr>
<tr>
<td>- Visualizing which parts dissipate more or less heat.</td>
</tr>
<tr>
<td>- Mainly used to make nice pictures for customers.</td>
</tr>
<tr>
<td>Testing</td>
</tr>
<tr>
<td>- Making tests based on the latest insights.</td>
</tr>
<tr>
<td>- Testing under different conditions.</td>
</tr>
<tr>
<td>- Testing different concepts (active cooling vs. passive cooling, size of heat sink, airflow of fan and extreme conditions (hot room))</td>
</tr>
</tbody>
</table>

Table 3.5: Analysis and testing topics in a development project.

is significant in natural convection systems.”

**Hiring an expert**  Industrial design engineers outsource specialist calculations, such as RC-networks, CFD or FEA simulations, to thermal design experts. Although such an analysis is comprehensive, the practical use is not always confirmed. Participant 14 explains, “In the beginning, we let a specialized company make us a theoretical model, but this was too complex and based on such assumptions that we could not do anything with it.” It appears that the industrial designer must therefore have some insight into basic heat transfer mechanisms in order to understand the value of a detailed analysis, especially when the analysis is outsourced to a thermal design specialist.

**Analysis process**  The process of analysing a design during concurrent development described by Participant 14, who explains not only the possibilities for outsourcing the analysis, but also the critical issues encountered, is shown in table 3.5.

**Causes of heat dissipation**  There are several causes of heat dissipation that play a role in design. In the area of analog systems (household goods and electric tools), steering transistors (in drive circuits), electromotors and heating elements dissipate a great deal of heat. The main driver and point of attention in such products are current draws in the circuit. For designers, this is the first element that must be recognized. Apart from this, each component has a specific current draw, derived from handbooks or data sheets. The designers, usually electronic designers, obtain rough calculations for the power dissipation of the most critical components.

The high currents in electromotors can impair connections by char-forming resulting from sparks. This can result in higher resistance and hot components. According to Participant 4, “Heat problems usually occur in under-dimensioned electromotors. For example, an electromotor in a cassette player is over-dimensioned and does not produce much heat, contrary to the electromotor in an electric drill, which is under-dimensioned and can develop a lot of heat.”
Power supplies are also recognized as important components that must be observed. Participants 8, 9, 10 and 11 all state that the general efficiency is approximately 10%, which means that this amount of total power conversion is dissipated heat. In addition, these participants also state that the power dissipation in components is often difficult to predict and that the location of a component (physical location) also influences its power dissipation.

**Measurement/prototyping**  Measurements play an important role in thermal design. Measurements are completed by using thermocouples or sometimes, an infrared camera. During the interviews, the importance of measurements was discussed. It could be concluded that for most designers, the measurements of a thermal mock-up are more important than results from a CFD or FEA analysis, because CFD software is often not available. Therefore, a CFD analysis is sometimes outsourced to a specialist. This does not account for the thermal design specialist, to whom CFD is available and who is accustomed to its use in thermal design.

Measurements are important for verifying boundary conditions in a thermal model. In products with complex convection properties (such as parts moving at a variable speed), the execution of a reliable CFD analysis is virtually impossible. In some cases, measurements are combined with resistor network modeling. Participant 15 states, "Resistor networks work very good; you do, however, need to derive boundary conditions from measurements. Without such measurements, this is almost impossible."

In most cases, a thermal mock-up or functional model (FUMO) is used to measure the effects of design variables. In the mock-up, the effects of power dissipation of, for instance a PCB on a critical component or module, is simulated. Measurements are executed by using a heat foil or resistors to simulate heat dissipation. In some cases, such as those described by Participant 17, real modules are used during mock-up measurements. Infrared measurements are sometimes used. The need for this is not always described in a positive manner. According to Participant 14, "We also used infrared measurements to see where the heat escapes the device. In the development process, however, these measurements were really not of any use and are seen more as a means to communicate results to management."

Some participants gave a specific description of the mock-up process used in their development process. Participant 15 said, "In the beginning of a project we measure with a model and use heat foils to simulate the printed circuit board. Later, when hardware is available, we use working models. Obviously, we also do simulations to estimate heat transfer coefficients with a thermal spreadsheet. With experiments, we can determine how the temperature of critical components relates to the temperature of one specific sensor. At a certain point in time, we could determine the exact temperature by just measuring in one place. All of this is based on experiments. When the boundary conditions are better defined, you can do good approximations with less experiments. Without experiments, it continues to be guesswork."

Participant 17, a thermal design specialist, is experienced in the use of thermal design mock-ups. Thermal designers generally have CFD software available and know
how to efficiently combine software analysis and measurements. Regarding comparisons between software and measurements, Participant 17 describes the following: “The advantage of using hardware measurements, compared to CFD, is that you can correctly model complex modules. Software, however, is more flexible and easier to use for a trend analysis”.

### 3.3.3 Problems from a practical point of view

This section describes examples of practical problems in thermal design described during the interviews.

The first problem is a lack of thermal knowledge among mechanical and electronic designers. Participant 4 describes, “The designers, in this case, students who are designing a household tool of some kind, do not have any clue on how to solve thermal design problems. The availability of simple calculation models would be a welcome addition to the design process in the design of this category of products.” Participant 14, who works in a company that develops electronic products, further describes, “Our knowledge is mainly grounded in experience. Finding external experts who use a pragmatic approach is difficult. Theoretical models are often complex and unpractical”.

The second problem is that temperature is often neglected. According to participant 16, “My experience is that temperature is more an underestimation by the electronic designer, rather than by the mechanical designer. Unfamiliarity with the subject is the problem with electronic engineers. They just suppose that we will resolve the problem. In most cases therefore, heat problems show up when the prototype is being tested.” Participant 17 is also familiar with temperature neglect. He states, “If a cooling problem is neglected, you receive after-defect solutions.”

### 3.3.4 The need for easy-to-use formulas

At the end of the interviews, the issue of improving thermal design by developing easy-to-use formulas was discussed, where several remarks were made. For instance, Participant 9 describes the possibility of loss density: “Loss density could be a good first order indication in design”.

Other participants, including novice industrial designers, confirm the idea that there is a need for easy-to-use formulas. Participant 13 indicates, “Rules of thumb and a simple model would be convenient; reading values from a table, for instance, would be practical. Input should, in my opinion, include power dissipated by a component, conduction in the print and the maximum temperature of components.” In addition, Participant 14 describes the following: “We could benefit from having simple formulas. Personally, we could really use a small manual or handbook that contains some rules of thumb that are easy to use. It would be better to be able to do some estimations before calling the manufacturer. It also increases the value of making infrared measurements; you would, for instance, know what you can do with them before they are measured”.

Experienced design engineers are generally more convinced of their ability to solve heat problems. Participant 15 indicates that “Someone that does not know much about
temperature could use such a thing very well; for me, it would be of no use because I have much experience”. Another experienced design engineer, Participant 16, explains the following: “Such a formula would be mainly helpful for recognizing the problem. If during the process the energy dissipation turns out to be twice as high, then you can have many formulas, but all aspects that are in the formula must help solve the problem, including material choice and active versus passive cooling. It can be helpful to at least fix the properties of the design in the early stage, making it even more clear that if heat is above a certain value, you have to use active cooling”.

The discussion with Participant 17, a thermal design expert, focuses more on the development of new concepts. Participant 17 points out that there is a knowledge gap: “So, the question is how we can come from a vision of the future to working modules that can be sold to customers. This is the essence of the gap between design and product realization”. The disadvantage of working with standard modules in design is also explained: “The industrial designer has an ideal image of how the product must look; however, the modules and power source partly kill the idea. You can integrate the design vision for the future by giving attention to how to change the modules so that the functionality is maintained and the original idea can be developed as good as possible”. Participant 17 concludes his vision by proposing the following ideas: “If you know now what will be the trend in industrial design, then you could look on module level and system level to the consequences. For example, how a power supply unit is designed and what the engine should look like and how the shape factor of my PCB must change to realize the required shape factor”.

3.4 Interpretation and conclusion

Industrial designers can comprehensively define thermal design requirements for a particular project. Usually, manufacturer specifications describe the maximum allowed temperature and also give indications for power dissipation and thermal resistance so that the designer can determine if components will be able to fulfill their requirements. The criteria, with regards to ergonomics and an ambient environment, are also easily defined by safety regulations, such as the IEC degrees of protection provided in the enclosures [26].

Design variables are recognized by designers. Participants are familiar with choices, such as where components are positioned, encasing material, open/closed encasing, active or passive cooling, choosing components that are more energy-efficient, cooling fins, heat pipes and gap filler materials. Generally, a design is based on a designer’s experience. Designers use manufacturer specifications, magazines or the Internet to find the most optimal solutions. Designers more involved in thermal designs include power electronics researchers (participants 7-11) and thermal design experts (participants 1, 17), who are all familiar with available solutions.

Interview responses also indicate that the thermal design aspect in product development is highly based on tacit knowledge. For thermal design specialists, this is not a problem because they are involved in the subject on a daily basis. For the industrial designer who is less frequently involved in thermal design, it is difficult to obtain a good
overview of available design variables, especially evaluations of different options. In addition, industrial design engineers do not have the insight or knowledge to evaluate basic solutions, making them dependent on manufacturers when choosing solutions.

Designers are generally unfamiliar with heat transfer concepts, including thermal resistance, heat transfer coefficients and first order temperature approximations. There are exceptions, such as thermal design specialists, who are proficient and experienced in thermal analyses (participants 1, 15 and 17). Approaches, in many cases, include ‘guesswork’ based on experience. There are two probable causes for this. First, this results from a lack of thermal design education. Second, this results from an inefficient match between everyday design practice and available thermal design models and methods. This was outlined in several interviews.

A designer not experienced in thermal design finds it difficult to predict the effects of design changes on temperatures for a device. Therefore, this type of designer spends a great deal of time making thermal mock-ups using different configurations in order to compare effects of design decisions. For most industrial design engineers, measurements determined using a thermal mock-up or functional model are valuable for thermal designs. The thermal design specialist realizes that approximations executed using handbooks or computed using computational fluid dynamics must eventually be verified with actual measurements.

Different views indicate how practicing designers work in the field of thermal design. Three key issues derived from interviews and literature include the following:

1. Designers are unfamiliar with heat transfer and thermal design theories. Such designers lack the basic knowledge that would enable them to make basic design choices and evaluate how important temperature is to the design. The choice between passive and active cooling is currently based on experience and trial and error.

2. An evaluation of structural concepts on temperature development is not supported by a standard approach.

3. Temperature measurements for mock-ups and functional models are crucial in thermal design practice for finding reliable boundary conditions, but are time-consuming. The process of measuring could possibly be optimized by properly integrating easy-to-use formulas that could be calibrated using measurements determined from a thermal mock-up or functional model. The effects of design changes could be predicted by pre-defined rules of experience and estimations.

Furthermore, as has been concluded from studying the literature and has been clearly expressed by participants during interviews, any tool used for conceptual design should be easy to use. To resolve the three issues listed above, models are needed that contain the following three characteristics:

Model 1 supports risk assessments put forth by the designer, even if he or she has no knowledge of heat transfer or thermal design.
Model 2 supports finding and analyzing the main heat path in structural concepts and is useful for estimating rough temperatures in an electronic product.

Model 3 supports the determination of the total transient behavior in a device.

The following chapters will focus on the development of the three models and on methods for applying them. The models will finally be evaluated by means of a usability experiment and in-depth interviews.
CHAPTER 4

Design model 1: Evaluating active vs. passive cooling

On the basis of an empirical study on existing products in combination with heat transfer calculations, a model has been developed that can be used to evaluate passive vs. active cooling in conceptual designs for electronic products.

<table>
<thead>
<tr>
<th>Model development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 4</td>
</tr>
<tr>
<td>Design model 1:</td>
</tr>
<tr>
<td>Evaluating active</td>
</tr>
<tr>
<td>vs. passive cooling</td>
</tr>
</tbody>
</table>

| Chapter 5          |
| Design model 2:    |
| A generic resistor |
| capacitor network  |

| Chapter 6          |
| Design model 3:    |
| A back of the      |
| envelope formula   |
4.1 Introduction

Product designers have indicated in interviews (chapter 3) that one of the most basic thermal design choices they have to make is deciding between active and passive cooling. In this chapter, the following question will be answered: What is the most basic and simple method that can be developed for a first order thermal design evaluation of active vs. passive cooling? In addition, a new model that supports this idea will be introduced. Furthermore, this model provides a guideline showing when thermal design creates a bottleneck in the development process. This issue is especially important to communication between mechanical engineers and hardware engineers because it shows the effects of power dissipation on mechanical design. The model is based on empirical measurements and heat transfer calculations. The model described in this chapter is the most simple thermal design model possible. For those cases where a more detailed analysis of temperature in an electronic product is needed, a generic model will be described in chapter 5, along with a back-of-the-envelope approach in chapter 6.

This chapter begins with an approach using model 1, as described. The following section describes a theoretical model for the cooling limits of an electronic product. The results for measurements of existing products are described. This section is followed by a discussion in which measurements and calculations are compared. The chapter finishes with a description of the practical application of the models and concluding ideas.

4.2 An approach for model 1

In the approach for model 1, basic heat transfer calculations are combined with measurements for existing products. Heat transfer calculations show maximum boundary conditions of heat transfer for a surface area. This is done using several surface temperature differences within the environment. Measurements combined with these values show a transition area that can be used as a guideline for a particular design. In this chapter, five steps that define the model will be listed.

Step 1: The passive cooling limit of a product. Defines theoretical passive cooling limits for several temperature differences between the surface of a product and the environment.

Step 2: Measurement results. Measures power, surface area and hotspot temperatures on existing products.

Step 3: Discussion. Discusses boundary and transition areas between passive and active cooling.

Step 4: Applying model 1 to design. Describes how the model can be practically used in a design situation.

Step 5: Conclusions and recommendations. Draws conclusions from research described in this chapter.
4.3. THE PASSIVE COOLING LIMIT OF A PRODUCT

Here, the theoretical approximation of passive cooling limits for an electronic product is explained. The theoretical cooling limit is derived by combining convective and radiative heat transfer coefficients from an isothermal surface to an ambient environment. Calculations are compared to measurements of existing products, which will be described in proceeding sections.

4.3.1 Model definition

Passive cooling limits have been calculated for several temperature differences between a hot surface with an ambient environment by using Nusselt correlations for a vertical plate. By comparing these values with measurements for existing products, boundary areas for the passive and active cooling of an electronic product and a maximum power-to-area ratio for electronic products can be defined.

These calculations are for heat transfers between an isothermal surface temperature $T_e$ and the ambient temperature $T_a = 296K (~23^\circ C)$. A specific dimension for a vertical plate $L_c$ of 0.1m and thermal conductivity of air $k_{air}$ is used to calculate the heat transfer coefficient for convection $h_c$ and the heat transfer coefficient for radiation $h_r$ at temperature differences $\Delta T (T_e - T_a)$ of 5K, 15K and 25K (table 4.1). The temperature difference of 15K is comparable with previous studies found in literature [70]. The temperature differences of 5K and 25K define a transition area between passive and active cooling.

The heat transfer coefficients $h_c$ and $h_r$ have been approximated based on the standard heat transfer theory for a vertical plate with an isothermal temperature distribution across the surface. To determine $h_c$, the Hilpert correlation (equation 4.3.1) [54] has been used to approximate the Nusselt number $Nu$.

$$h_c = \frac{k_{air} \cdot Nu}{L} [W/(m^2 \cdot K)]; \quad Nu = 0, 54Ra^{0.25}$$

The heat transfer coefficient of radiation $h_r$ is determined by using the average temperature $T_{av}$ for convenience and is derived from the general formula for radiation heat transfer (equation 4.3.2). Here, $q_r$ is the radiation heat transfer [W], $\epsilon = 1, 0$ is the emissivity of the radiating surface, $\sigma$ is the Stefan-Boltzmann constant $[5.67 \cdot 10^{-8}]$, $F_{1.2}$ is

### Table 4.1: Natural convection and radiation heat transfer coefficients for different temperature differences. Calculated using equation 4.3.1 and equation 4.3.2 for an ambient temperature $T_a = 296K$.

<table>
<thead>
<tr>
<th>$h_c$ [W/(m²·K)]</th>
<th>$\Delta T=5$ K</th>
<th>$\Delta T=15$ K</th>
<th>$\Delta T=25$ K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_r$</td>
<td>6.0</td>
<td>6.3</td>
<td>6.7</td>
</tr>
<tr>
<td>$h_c$</td>
<td>3.7</td>
<td>4.9</td>
<td>5.5</td>
</tr>
<tr>
<td>$h_{tot}$</td>
<td>9.7</td>
<td>11.2</td>
<td>12.2</td>
</tr>
</tbody>
</table>
the radiation shape factor, \( A \) is the radiation surface area, \( T_1 \) is the surface temperature of object 1, \( T_2 \) is the surface temperature of object 2 and \( T_{av} \) is the average surface temperature between object 1 and object 2.

\[
q_r = \epsilon \sigma F_{1,2} A (T_1^4 - T_2^4) \quad \Rightarrow \\
q_r = \epsilon \sigma F_{1,2} A (T_1^2 + T_2^2)(T_1 + T_2)(T_1 - T_2) \quad \Rightarrow (4.3.2)
\]

For \( T_1 \approx T_2 \approx T_{av} \):

\[
h_r = \epsilon \sigma F_{1,2} (T_{av}^2 + T_{av}^2)(T_{av} + T_{av}) \quad \Rightarrow \\
h_r = \epsilon \sigma F_{1,2} A 4T_{av}^4 [W/(m^2 \cdot K)] (4.3.3)
\]

Values and properties for these variables can be found in standard heat transfer literature [24]. The conductive heat transfer coefficient measured from the encasing exterior to the environment is supposedly negligible. The resulting total heat transfer coefficient \( h_{tot} \) is then calculated by summarizing \( h_c \) and \( h_r \).

Table 4.1 gives results for the three temperature differences described above. The results show that \( h_c \) is significantly dependent on temperature differences between the surface and the environment, while \( h_r \) is not. In addition, it can be concluded that in passive cooling, radiation heat transfer can play a significant role because it is in the same order and magnitude as convection heat transfer. However, this only accounts for black and graybody radiation, where \( \epsilon \approx 1, 0 \).

### 4.4 Measurement results

In this section, the results of experimental measurements on existing products are described. In order to compare measurements to the theoretical values, measured products are classified into three categories: passively cooled products, actively cooled products and heating products. In a fully enclosed configuration, passively cooled products mainly release their heat through the surface area of the encasing. If there are ventilation holes in the product, then heat transfer through the encasing is combined with airflow (through natural convection), which is often combined with cooling fins inside the product, for example, an LCD TV. Actively cooled products use forced air flow (a fan) for temperature control. Products that use heating as a function, for example, a toaster or water cooker, are usually designed to withstand high temperatures.

#### 4.4.1 Experimental method

Power dissipation \( q \) and area of the minimum enclosing box \( A \) of 66 electronic products has been measured (Figure 4.1). The sample of this test contains 13 actively cooled products, 47 passively cooled products and six products containing a heating element. To gain more insight, measurements of the steady-state temperature of the hotspot \( T_h \) have been included in the measurements for a set of 21 products. The sample of this test contains 16 passively cooled products and five actively cooled products. Products with a
4.4. MEASUREMENT RESULTS

heating element are specific because their function is explicitly to produce and transfer heat.

Using measurements, $T_{av}$ has been derived, which is needed to calculate heat transfer coefficients for radiation and convection. All temperatures are measured during a steady-state situation. The surface area has been approximated by measuring the area of the minimum enclosing box $A$ of the products. T-type thermocouples are attached to those locations where the hotspot is expected. Figure 4.2 shows three product examples.

### 4.4.2 Power and area measurement results

The surface area $A$ and power dissipation $q$ has been measured for 66 product total. Figure 4.1 presents both the calculated heat transfer lines and positioning of the experimental results. The interpretation of experimental results shows a separation between passively and actively cooled products. This includes the line belonging to a 15K temperature difference between the encasing temperature and the ambient temperature.

To the best knowledge of the author, a transitional area in the passively cooled area below 15K and the actively cooled area above 15K is proposed here. Two temperature
Figure 4.2: Examples of hotspot measurements. Thermocouples attached to the hotspot inside the encasing measure $T_h$ of a PDA, car vacuum cleaner and AC-DC adaptor.

Lines have been added, one that represents a $5K$ and one that represents a $25K$ temperature difference between the encasing and ambient temperatures. In the following paragraphs, these temperature ranges will be compared to power, area and hotspot measurements.

The values of $A$ varied between $8.0 \cdot 10^{-3} m^2$ (portable radio) and $3.0 m^2$ (washing machine), while $q$ varied between $2.0 \cdot 10^{-2} W$ (portable radio) and $2.0 \cdot 10^3 W$ (water cooker). Figure 4.1 shows that most products which dissipate less than $1W$ of power are positioned below the $5K$ temperature line. Product examples in this range include a diskman, radio, MP3 player and minidisk. It is highly probable that thermal design was not a major issue in the development of these products. Examples of products that are positioned around the $5K$ line up to the $15K$ line include stereos, cathode ray tube TVs, LCD TVs, network switches and routers. It would be likely that thermal design played a significant role in the design process of these products. For instance, an LCD TV uses holes in the encasing, combined with a significant amount of cooling fins on the inside of the product, to dissipate heat from the printed circuit board to an ambient environment.

In the ‘actively cooled’ range, between the $15K$ and $25K$ lines, products, such as a laptop, are positioned. These types of products are generally regarded as in critical need of proper thermal design. In the area above $25K$, products, such as power tools, kitchen appliances and slide projectors, can be found. Power tools that use an electromotor usually have a relatively short duty-cycle and, therefore, generally do not reach their steady-state temperature. Products that are convectively cooled are cooled by airflow induced by a rotating component, sometimes a fan directly connected to the electromotor. Other products in this range, such as kitchen appliances and slide projectors, generally give off a great deal of heat. Thermal design is very critical in these type of products. Temperatures of hotspots in these types of products are usually much higher than in products within the range of $15K$ to $25K$.
4.4.3 Hotspot temperature measurement results

For 21 products, the temperature $T_h$ of the hotspot - typically an electromotor, transistor or integrated circuit - was measured during the steady-state (figure 4.3). The surface area of the product’s minimum enclosing box and the amount of power consumption is included in figure 4.3. The ratio $q/A$ is a measurement of the area-specific power of the product. Temperature differences for $5K$ include $q/A = 49[W/m^2]$; for $15K$, differences include $q/A = 168[W/m^2]$; and for $25K$, these differences equal $q/A = 303[W/m^2]$. Finally, a temperature line of $T_h = 70^\circ C$ is included. In thermal design, the critical temperature of many components lies above this value [39]. This study proposes taking this hotspot temperature into account as a reference value.

From figure 4.3, two items can be noticed. First, the temperature of the hotspots seems to increase when the ratio $q/A$ increases. This includes passively cooled products, as well as actively cooled products. Second, hotspot temperatures above the reference value of $70^\circ C$ are positioned between the $5K$ line and $15K$ line for passively cooled products and above the $25K$ line for actively cooled products.

4.5 Discussion

One decision made during the development of thermally critical designs is whether or not to use active cooling to prevent the encasing from reaching an unacceptable temperature. A first-order exploration of this issue has been supported by taking into account the maximum limit of passive cooling for several temperature differences and comparing the results with measurements of actual products.

From the results described in the previous sections, certain electronic products, such as the microwave oven, toaster and car vacuum cleaner, cannot be passively cooled through the encasing. The $\Delta T$ would result in either too large of a surface area or encasing temperatures above international safety standards [27]. In practice, products with
such a high power density are either insulated from the user (toaster) or cooled by forced convection (microwave and vacuum cleaner).

On the basis of figure 4.1, a transitional area that requires attention can be defined. If $\Delta T$ is in between $5K$ and $25K$, a transition appears between simple passive cooling and comprehensive active cooling. Based on figure 4.3, the designer must be careful when applying passive cooling between the ranges of $5K$ and $15K$. Active cooling may be applied between $15K$ and $25K$ with confidence. Active cooling above the $25K$ line, however, requires an extensive study in thermal design.

Heating products place high on the graph in the area of forced convection, representing high area-specific power and high surface temperature, typical for these types of products. These products do in fact have either a fan (microwave) or shut down upon reaching a certain temperature (water cooker), which explains why area-specific power for these products can be so high.

4.6 How to apply model 1 in design

Model 1, presented in figure 4.4, gives guidelines that can be used to evaluate if passive cooling for a product is feasible. These guidelines can be applied by estimating power consumption and the surface area of the minimum enclosing box. Depending on the type of product, the probability that a critical hotspot temperature will occur in the design may be predicted.

Products in zone 1 (see figure 4.4) appear to be actively cooled and have a high possibility of having hotspots (see figure 4.3). In this case, a detailed thermal analysis is advised. In zone 2, the products are actively cooled and relatively secure regarding hotspots. Products in zone 3 appear to be passively cooled and have a high chance of having hotspots. Here, a detailed thermal analysis is also advised. In zone 4, the products are passively cooled and relatively secure regarding the occurrence of hotspots.

The application of this model is twofold. First, the model is to be used during the very early stages of design (conceptual phase) to gain insight into whether or not the use of active cooling is necessary. The designer begins by defining the ratio $\frac{q}{A}$. Then, he or she continues with positioning the design in the graph or comparing the results to the rule of thumb, described above. The analysis ends when a decision is made on whether or not a fan will be used in the design (active cooling) and with an assessment of whether a detailed thermal analysis in subsequent design phases is needed. Second, the rule of thumb can be used as a means of communication between design and electronics engineers. The design team can use the graph to benchmark their products, comparing them to those of competitors, and define targets with regards to new or developed products. For comparable studies, see Yazawa et al. [70].

In some cases, a graph can be difficult to read, especially when products are on the boundary line between two areas. Therefore, a new measure is proposed that equals the ratio $\frac{q}{A}$. If the ratio $\frac{q}{A}$ changes when compared to previous designs through either an increase in power consumption or a reduction in product surface area, then the designer and electronic engineer must again assess the product on the basis of the rule of thumb.
4.6. HOW TO APPLY MODEL 1 IN DESIGN

and estimate whether or not a change in design or a more extensive thermal analysis is required.

By examining temperature lines, corresponding ratios of $\frac{q}{A}$ can be derived. These include 5K, with a ratio of $\frac{q}{A} \approx 50$, 15K, with a ratio of $\frac{q}{A} \approx 150$ and 25K, with a ratio of $\frac{q}{A} \approx 300$. The designer can obtain some insight on whether a detailed analysis of temperatures within the product is necessary, based on a simple rule of thumb. However, the following does not apply to the development of heating products (e.g., toaster, watercooker, etc.). A different approach other than that presented here must be taken into account.

The model is applied as follows for a given design:

1. Estimate $q$ and $A$ of your design.

2. Determine in which of the zones in figure 4.4 your design is positioned.

   (a) If $\frac{q}{A} > 300$, the design lays in zone 1 and active cooling, with a detailed thermal analysis, is essential.

   (b) If $300 > \frac{q}{A} > 150$, the design lays in zone 2 and active cooling can be used with a low thermal risk.

   (c) If $150 > \frac{q}{A} > 50$, the design lays in zone 3 and passive cooling is an option, but a detailed thermal analysis is essential.

   (d) If $50 > \frac{q}{A}$, the design lays in zone 4 and the product can be passively cooled.

3. Make decisions, set criteria and reuse the model when significant design changes in $q$ or $A$ occur.
4.7 Conclusions and recommendations

A simple model has been developed with practical applications for first-order exploration of thermal designs for electronic products. The model gives an indication of whether or not the existing concept demands a more detailed exploration of temperature development within the device. The model can also be used by the designer to discuss if it is theoretically possible to naturally cool the product dependent on safety standards. The model can be effectively used in the primary exploration of the thermal design of an electronic product during product development. In the final chapters of this thesis, the usability of the model, its applicability, efficiency and quality will be verified.

The model described in this chapter is based on electronic products that are used at conventional ambient temperatures. There are, however, limitations for the model. With specific design criteria with regards to encasing temperature, extreme situations, such as high or low temperature environments and the effect of changing altitudes on the presumed heat transfer coefficients have not been taken into account. This thesis will not incorporate these aspects into the model, but may be taken into account in future studies.
CHAPTER 5

Design model 2: A generic resistor capacitor network

This chapter answers the question *Can one generic model be used to theoretically estimate the temperature in the heat path in an electronic product?* This solution is focused on the development of a one-dimensional resistor capacitor network model that can be used to calculate transient hotspot temperature development in an electronic product.

| Model development | Chapter 4 | Design model 1: Evaluating active vs. passive cooling? | Chapter 5 | Design model 2: A generic resistor capacitor network | Can we make one generic model that can be used to theoretically estimate the temperature in the heat path in an electronic product? | Chapter 6 | Design model 3: A back of the envelope formula | Can we develop a concept for formulas that can be used in combination with measurements on a full working model or thermal mock-up? |


5.1 Introduction

In the previous chapter, a model was demonstrated (model 1) that could be used as a rule of thumb during the very early stages of conceptual design. The model can be easily applied and gives good direction. However, it does not result in an actual hotspot and encasing temperature approximation. Preliminary research shows that there is a need for a more detailed analysis during the later stages of conceptual design (chapter 3). This approximation is needed to ensure that a component does not reach above the maximum allowed temperature, as specified by its manufacturer. In addition, this assessment would determine if the product meets ergonomic specifications for the encasing temperature. Therefore, the following question is discussed in this chapter: Can one generic model be used to theoretically estimate the temperature of the heat path in an electronic product?

It is important to clearly state that the aim of the model described in this chapter—as well as in other chapters—is to evaluate what the proper direction is for improving thermal design during the conceptual phase of a product creation process. It is not the aim of this study to develop a generic model for all types of products. Instead, the intention is to define a model and method and practically apply the model that shows the best opportunities for further configurations, other than a passively cooled closed encasing. The verification chapters at the end of this project will elaborate more on this issue.

Because designers deal with duty cycles in an electronic product, a transient model has been developed. The result is a resistor-capacitor model in the form of a Lagrangian state space equation that can easily be numerically approximated and is easy to use to determine transient temperature calculations. One requirement is that the present model should give at least a ±20% estimation of encasing and hotspot temperatures.

This chapter will result in a model that can be easily implemented by means of a software program. However, limitations of this approach include that boundary conditions must be calculated from basic heat transfer theory, which results in only a rough approximation. Despite this weakness, this is sufficient for first-order temperature estimation. This issue will be improved throughout the next chapter, where boundary conditions are generated from measurements on a fully working model or thermal mock-up.

After a description of model 2, this chapter will discuss the description of the generic resistor capacitor network and the derivation of state space equations. The chapter follows with a section in which the model is applied to a AC-DC adaptor. Finally, a section is added in which a description of how to practically use the model throughout a design is given. The result is a model that calculates temperature within the targeted 20%. Limitations of the model include a generalization for passively cooled products with a closed encasing. Additional research with the aim of extending the application area will be needed to address this issue.

\[ \text{1The 20% criterion is advised by a product development manager from an international organization with 35 years of experience} \]
5.2 Approach of model 2

For model 2, a resistor capacitor network is developed and programmed into a small software program. The industrial designer can use this program to fill in variables and calculate temperatures. In this chapter, five steps will be listed to define and calibrate the model.

**Step 1: Model development**  Develop a model for the temperature in an electronic product in the form of a resistor capacitor network (RC-network) and derive the state space equations. These state space equations can be used to calculate the temperature for several areas within the product.

**Step 2: Results**  Approximate the temperature in an example product by using state space equations. In this case, an AC-DC adaptor has been used. Required heat transfer variables are derived from standard conduction, convection and radiation equations. The section follows with a description of the measurements and results that are completed for the sample product for several ranges of power dissipation.

**Step 3: Discussion**  Compare the measurements and approximations. The difference between the measured and calculated values is discussed and directions for improving the accuracy of the model are given.

**Step 4: Practical application**  Describe the practical use of the model in a design situation.

**Step 5: Conclusions and recommendations**  Draw conclusions from the research described in this chapter.

5.3 Model development

As a basis for the model, this paper examines an electronic product as one single hotspot within an encasing. In reality, the hotspot can include a power dissipating component, such as a coil, an integrated circuit (IC) or the components of a printed circuit board (PCB). Based on this abstraction, various models can be derived, ranging from a very simple resistor capacitor network (RC-network), which will be discussed in this chapter, to a complex network of thermal resistors and capacitors. In this section, mathematical relations of the one-dimensional heat transfer will be derived. This is done by proposing a one dimensional RC-network that can be applied to a variation of electronic products that are passively cooled and have a closed encasing. Based on insights gained through this analysis, the mathematical model may be expanded into something more complex. This will be explored in future research if further details are required.

5.3.1 Description of the thermal RC-network

In this paragraph, a model helping with temperature prediction in an electronic product in the form of a thermal RC-network will be derived (figure 5.1). When designing
electronic products, it is important to predict the behavior of a product within a certain period of time. For this particular model, it is necessary to take into account transient temperature development. By using transient temperature prediction in the form of state space equations, the model allows for the option of evaluating a usage scenario. This usage scenario can then be evaluated and compared with defined criteria. Based on such results, the product can be properly designed without over-dimensioning, which would bring about higher costs.

The system consists of five types of variables: thermal resistors $\theta$, temperature $T$, thermal capacitors $C$, heat flow $q$ and energy $E$. Four thermal resistors include the following:

1. The core of the hotspot to the surface of the hotspot, or $\theta_1$
2. The hotspot surface to the interior surface of the encasing, or $\theta_2$
3. The interior surface of the encasing to the exterior surface of the encasing, or $\theta_3$
4. The exterior surface of the encasing to the ambient environment, or $\theta_4$

The temperatures in the product result from the hotspot heat flow $q$ and the thermal resistors, $q = \theta \cdot \Delta T$. In this model, five temperatures are defined:

1. The temperature inside the hotspot, or $T_c$
2. The temperature of the hotspot surface, or $T_h$
3. The temperature of the interior surface of the encasing, or $T_i$
4. The temperature of the exterior surface of the encasing, or $T_e$
5. The ambient temperature, or $T_a$

In order to calculate transient temperature development, thermal capacity must be taken into account. Generally, electronic products consist of an encasing on the outside and electronics on the inside. Between the electronics and the encasing, there is generally air. Usually, this means that when a product is heated, there are three thermal capacitors (figure 5.1) that cause temperatures to rise at a steady rate:
5.3. MODEL DEVELOPMENT

1. The thermal capacitance of the hotspot, or $C_1$
2. The thermal capacitance of the inside air, or $C_2$
3. The thermal capacitance of the encasing, or $C_3$

The main heat flow in the system, $q$, causes temperatures to rise. Three heat flow paths into thermal capacitances result from this general heat flow. The heat flow into these three thermal capacitances are defined as follows:

1. Heat flow into $C_1$, or $q_1$.
2. Heat flow into $C_2$, or $q_2$.
3. Heat flow into $C_3$, or $q_3$.

The heat flow in the model will result in four basic temperature differences:

1. From the core of the hotspot to the surface of the hotspot, or $T_c - T_h$.
2. From hotspot surface to the interior of the encasing, or $T_h - T_i$.
3. From the interior of the encasing to the exterior of the encasing, or $T_i - T_e$.
4. From the exterior of the encasing to the ambient environment, or $T_e - T_a$.

By combining these temperature differences, other temperature differences can be derived, for example, the temperature between a hotspot surface and exterior encasing, $T_h - T_e$, equals $(T_h - T_i) + (T_i - T_e)$. For practical reasons, only the temperatures $T_h$, $T_e$ and $T_a$ will be measured and compared, with resulting temperature differences of $T_h - T_e$, $T_e - T_a$ and $T_h - T_a$.

Finally, the total energy stored in the capacitances in the system can be defined by the product of thermal capacitance and temperature, or $E = CT$. However, in the present case, of greatest interest are temperature differences with regards to a reference temperature $T_a$. Therefore, the energy stored in the system will be defined as reference energies $E_{ref1} = C_1 T_a$, $E_{ref2} = C_2 T_a$ and $E_{ref3} = C_3 T_a$ for the following thermal capacitances:

1. Energy stored in $C_1$, or $E_1 = C_1 T_c - E_{ref1} \implies E_1 = C_1 (T_c - T_a)$.
2. Energy stored in $C_2$, or $E_2 = C_2 T_h - E_{ref2} \implies E_2 = C_2 (T_h - T_a)$.
3. Energy stored in $C_3$, or $E_3 = C_3 T_i - E_{ref3} \implies E_3 = C_3 (T_i - T_a)$.
5.3.2 Deriving state space equations

State space equations allow for the possibility of dynamically analyzing temperatures. A designer may use the equations to calculate temperature from any realistic starting condition. For instance, the model can be integrated and computed into a software program in which the designer fulfills required parameters and usage scenarios. The program then calculates temperature development in the device. This section will describe these state space equations and their parameters.

State space equations basically consist of two equations. The first equation defines air flow into thermal capacitances \( \dot{X}(t) = AX(t) + BU(t) \). The second equation is used to examine temperature differences \( Y(t) = CX(t) + DU(t) \). The matrices are defined as follows [38]:

- \( \dot{X}(t) \) are the heat flows into thermal capacitances.
- \( A \) is the system matrix and contains the values of thermal resistances and capacitances.
- \( X(t) \) is the vector describing the state of the system, which is the energy stored in thermal capacitances with regards to the reference temperature \( T_a \).
- \( U(t) \) is the input vector and describes the quantity of heat that flows from the hotspot into the system.
- \( B \) is the control matrix.
- \( Y(t) \) is the output of the system.
- \( C \) is the output matrix of the system.
- \( D \) is the feed-forward matrix.
5.4. RESULTS

State space equations can be derived by exploring the equations in the system. These can be defined as follows:

\[
\begin{align*}
E_1 &= C_1(T_c - T_a) \implies T_c - T_a = \frac{E_1}{C_1} \\
E_2 &= C_2(T_h - T_a) \implies T_h - T_a = \frac{E_2}{C_2} \\
E_3 &= C_3(T_i - T_a) \implies T_i - T_a = \frac{E_3}{C_3} \\
T_c - T_h &= \frac{E_1}{C_1} - \frac{E_2}{C_2} \\
T_h - T_i &= \frac{E_2}{C_2} - \frac{E_3}{C_3} \\
T_i - T_e &= \frac{E_3}{C_3} \left(\theta_i + \theta_a\right) \\
T_e - T_a &= \frac{E_3}{C_3} \left(\theta_i + \theta_a\right)
\end{align*}
\] (5.3.1)

State space equations based on this system can be defined as follows:

\[
X = \begin{pmatrix} C_1 T_c - E_{ref1} \\ C_2 T_h - E_{ref2} \\ C_3 T_i - E_{ref3} \end{pmatrix} ; \ X' = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} ; \ U(t) = q ; \ Y = \begin{pmatrix} T_c - T_h \\ T_h - T_i \\ T_i - T_e \\ T_e - T_a \end{pmatrix} .
\] (5.3.2)

\[
\dot{X}(t) = \begin{pmatrix} -\frac{1}{C_1} \theta_i & 0 & -\frac{1}{C_2} \theta_i \\ 0 & -\frac{1}{C_2} \theta_i & \frac{1}{C_2} \theta_i \\ 0 & -\frac{1}{C_3} \theta_i & \frac{1}{C_3} \theta_i \end{pmatrix} \left(\frac{1}{C_1} \theta_i + \frac{1}{C_2} \theta_i + \frac{1}{C_3} \theta_i\right) X(t) + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} U(t)
\] (5.3.3)

5.4 Results

In order to investigate the accuracy of state space equations and the assumptions made in the previous section, computations will be based on the properties of an actual product, in this case, a standard AC-DC adaptor (figure 5.2). Comparisons of the measurements with the model will give conclusions about the accuracy and applicability of the model for design engineering purposes. These computations have been carried out using a script written in C++. The measurements have been executed using thermocouples and an infrared sensor. Data has been collected by means of a data logger, which measures and stores the temperatures of the hotspot \(T_h\), the encasing \(T_e\), and the ambient temperature \(T_a\).
For the purposes of this comparison, both measurements and computations have been subjected to two different degrees of power dissipation, including 1W and 2W. The aim is to gain insight into what extent the model can predict variations in temperatures, depending on the different amounts of dissipated power.

### 5.4.1 Deriving heat transfer coefficients

Heat transfer coefficients are important for determining thermal resistors and thus, temperatures within a product. Basic formulas for deriving thermal resistors can be found in [33]. It is important to understand the influence of conductivity for materials making up the encasing and those surrounding hotspots, and the coefficients for radiation heat transfer and convection.

The heat transfer coefficients for convection and radiation are influenced by factors such as temperature differences and geometry. In this model, a combined heat transfer coefficient of 13.59 W/(m² · K) for convection and radiation is used. This derivation is given in equations 5.4.1 and 5.4.2. In this model, the Hilpert correlation (equation 5.4.1) [54] has been used to approximate the Nusselt number $Nu$. The heat transfer coefficient of radiation is approximated by using the average temperature $T_{av} = \frac{T_e - T_a}{2}$, emissivity $\epsilon$, the Stefan-Boltzmann constant $\sigma$ and the radiation shape factor $F_{1,2}$ (equation 5.4.2) [20]. In this study, the nonlinearity of the heat transfer coefficients will not be taken into account. This assumption is based on the following motivations:

1. It reduces complexity and computation time.
2. Although temperature does have an effect on all three types of heat transfer, it is assumed that the effect will be of significance only in cases of high temperature

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature, $T_s$ [K]</td>
<td>323.00</td>
</tr>
<tr>
<td>Ambient temperature, $T_a$ [K]</td>
<td>296.00</td>
</tr>
<tr>
<td>Average temperature, $T_{av}$ [K]</td>
<td>309.50</td>
</tr>
<tr>
<td>Kinematic viscosity, $\nu_{air}$ [m²/s]</td>
<td>17.77 · 10⁻⁶</td>
</tr>
<tr>
<td>Conductivity of air, $k_{air}$ [W/(m · K)]</td>
<td>27.61 · 10⁻³</td>
</tr>
<tr>
<td>Temperature coeff. of volume exp., $\beta_{air}$ [1/K]</td>
<td>30.94 · 10⁻⁴</td>
</tr>
<tr>
<td>Air Density, $\rho_{air}$ [kg/m³]</td>
<td>1.09</td>
</tr>
<tr>
<td>Absolute viscosity, $\mu_{air}$ [(N · s)/m²]</td>
<td>19.42 · 10⁴</td>
</tr>
<tr>
<td>Stefan-Boltzmann constant, $\sigma$ [W/(m² · K⁴)]</td>
<td>5.67 · 10⁻⁸</td>
</tr>
<tr>
<td>Emissivity of a radiating surface, $\epsilon$</td>
<td>1.00</td>
</tr>
<tr>
<td>View factor, $F_{1,2}$</td>
<td>1.00</td>
</tr>
<tr>
<td>Encasing width, $W_e$ [m]</td>
<td>44.00 · 10⁻³</td>
</tr>
<tr>
<td>Encasing height, $H_e$ [m]</td>
<td>35.00 · 10⁻³</td>
</tr>
<tr>
<td>Characteristic dimensions, $L$ [m] [(W_e + H_e)/2]</td>
<td>39.50 · 10⁻³</td>
</tr>
<tr>
<td>Prandtl number, $Pr$ [dimensionless] [(cp · $\mu$)/k]</td>
<td>70.82 · 10⁻²</td>
</tr>
<tr>
<td>Grashoff number, $Gr$ [dimensionless] [(L³ · $\rho$² · $\beta$ · g · $\Delta T$)/$\mu$²]</td>
<td>0.16 · 10⁶</td>
</tr>
<tr>
<td>Rayleigh number, $Ra$ [dimensionless] [$Gr$ · $Pr$]</td>
<td>0.11 · 10⁶</td>
</tr>
</tbody>
</table>

Table 5.1: Data for calculating $h_c$ and $h_r$. 

For the purposes of this comparison, both measurements and computations have been subjected to two different degrees of power dissipation, including 1W and 2W. The aim is to gain insight into what extent the model can predict variations in temperatures, depending on the different amounts of dissipated power.
5.4. RESULTS

One of the important starting points in thermal RC-networks is that a flow source \( q \) must be used instead of an effort source \( \Delta T \). This is because the models are dependent on the electronic product to dissipate power. It is impossible to practically enforce temperature for an electronic product so that it will dissipate a certain level of power.

\[
h_c = \frac{k \cdot Nu}{L} = 6,87\, [W/(m^2 \cdot K)]; \quad Nu = 0,54Ra^{0.25} \quad (5.4.1)
\]

\[
h_r = 4\epsilon \sigma F_{1.2} T_{av}^3 = 6,72\, [W/(m^2 \cdot K)] \quad (5.4.2)
\]

5.4.2 Solving state space equations

State space equations have been programmed using a C++ script in order to determine their solutions. The script is an algorithm based on the explicit Euler method for calculating differential equations (appendix B). The script can be used to develop a software program from which a practical application can be tested. This application consists of two parts:

1. The definition of the parameters and variables.
2. A while-loop that uses Euler approximation to numerically derive temperature differences over time.

Computations have been completed for 1W and 2W energy dissipation. From these computations, the resulting thermal resistors, capacitances and \( t_{98\%} \) (\( \approx 4 \cdot \text{timeconstant} \))

Figure 5.3: Measured and computed temperatures for 1W and 2W.
have all been derived. In addition, the ambient, encasing and hotspot temperatures have all been calculated. The results of the computed model and measured product are shown in figure 5.3.

5.4.3 Measurements on an AC-DC converter

The adaptor used in this study has been modified for the purpose of controlling the dissipated power by attaching a coil to an adjustable DC power supply. The computational and measurement data gathered have been processed in Microsoft Excel to derive steady-state temperatures, thermal resistances, thermal capacitances and the time at which the temperature reaches 98% of its steady-state temperature, or $t_{98\%}$. The value of $t_{98\%}$ may be used to determine the accuracy of computed thermal capacitances. The model takes into account several thermal resistors with the aim of calculating the four temperature differences resulting from five temperatures (figure 5.1).

Two tests on the adaptor have been carried out and include 1W and 2W heat dissipation. The ambient, encasing and hotspot temperatures have been measured. Table 5.2 shows the results of the model and measurements. $T_c - T_h$ adds only a small part to the total temperature difference, which is most likely due to the high thermal conductivity.
5.5 Discussion

In this paragraph, the results of the measurements and computations given in table 5.2 and figure 5.4 to figure 5.5 from the previous section will be discussed. The paragraph begins with some highlights and implications and then follows with some improvements for the model.

Previously, it was concluded that the temperature difference $T_h - T_e$ was significantly overestimated, while $T_e - T_a$ was underestimated. In order to examine the causes of large differences between measured values and computed values, several assumptions have been made to improve the predictability of the model. The effects that these assumptions have on the results are shown in figure 5.5. This topic will be discussed in the following section of this chapter.
CHAPTER 5. DESIGN MODEL 2

Table 5.2: Measurement and computation results.

<table>
<thead>
<tr>
<th></th>
<th>1W measurement</th>
<th>2W measurement</th>
<th>1W model</th>
<th>2W model</th>
<th>1W improved model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_1 [K/W]$</td>
<td>-</td>
<td>-</td>
<td>0,20</td>
<td>0,20</td>
<td>0,20</td>
</tr>
<tr>
<td>$\theta_2 [K/W]$</td>
<td>5,20</td>
<td>5,20</td>
<td>12,00</td>
<td>12,00</td>
<td>7,19</td>
</tr>
<tr>
<td>$\theta_3 [K/W]$</td>
<td>-</td>
<td>-</td>
<td>0,79</td>
<td>0,79</td>
<td>0,79</td>
</tr>
<tr>
<td>$\theta_4 [K/W]$</td>
<td>12,20</td>
<td>12,20</td>
<td>5,81</td>
<td>5,81</td>
<td>5,81</td>
</tr>
<tr>
<td>$C_1 [J/K]$</td>
<td>-</td>
<td>-</td>
<td>47,91</td>
<td>47,91</td>
<td>47,91</td>
</tr>
<tr>
<td>$C_2 [J/K]$</td>
<td>-</td>
<td>-</td>
<td>0,08</td>
<td>0,08</td>
<td>0,08</td>
</tr>
<tr>
<td>$C_3 [J/K]$</td>
<td>-</td>
<td>-</td>
<td>64,00</td>
<td>64,00</td>
<td>64,00</td>
</tr>
<tr>
<td>$t_{98%} [\times]$</td>
<td>3840</td>
<td>5280</td>
<td>4500 acc.17%</td>
<td>4500 acc.15%</td>
<td>3800 acc.1%</td>
</tr>
<tr>
<td>$T_i - T_h [K]$</td>
<td>-</td>
<td>-</td>
<td>0,20</td>
<td>0,40</td>
<td>0,20</td>
</tr>
<tr>
<td>$T_h - T_e [K]$</td>
<td>5,20</td>
<td>10,50</td>
<td>12,78</td>
<td>25,56</td>
<td>7,98</td>
</tr>
<tr>
<td>$T_e - T_a [K]$</td>
<td>12,20</td>
<td>22,60</td>
<td>5,80</td>
<td>11,61</td>
<td>5,81</td>
</tr>
<tr>
<td>$T_h - T_a [K]$</td>
<td>17,40</td>
<td>33,1</td>
<td>18,58</td>
<td>37,17</td>
<td>13,63</td>
</tr>
</tbody>
</table>

5.5.1 Highlights and implications

From the data, several conclusions can be drawn. We can see that $t_{98\%}$ can be estimated within an accuracy of 17%. $t_{98\%}$, computed with the model, appears to be a relatively good approximation with regards to the measured $t_{98\%}$. In addition, the model predicts the effects of temperature changes by observing changes in the concept, in this case, a change in power dissipation. The present results show that although measured and computed temperatures do not correspond, the temperatures of the computations do proportionally change with measured temperatures when dissipated power is changed from 1W to 2W. This is a positive effect, which shows that the model accurately predicts the effect of power changes on temperatures for a particular concept.

However, the results also show that temperature differences from a hotspot to the encasing and from the encasing to an ambient environment are incorrectly computed (figure 5.5). First, the measured $T_h - T_e$ and $T_e - T_a$ values (in figure 5.3-figure 5.5 these are squares and dots respectively) deviate a great deal from computed values. However, the sum of the two computed and measured values of $T_h - T_e$ and $T_e - T_a$, namely $T_h - T_a$, does not deviate a great deal. We can see that the model predicts the hotspot temperature with an accuracy of 8% to 21%.

The problem with the model is that the wrong computation for $T_i - T_h$ and $T_e - T_a$ are given. The cause of this miscalculation is an incorrect estimation of thermal resistances $\theta_2$ and $\theta_4$. $\theta_2$ has been computed too high, with a factor of 2,46 (12,78/5,20), resulting in a high estimation of $T_h - T_e$. $\theta_4$ has been computed too low, with a factor of 0,48 (5,80/12,20), resulting in a low estimation of $T_e - T_a$ (table 5.2. The remainder of this paragraph will discuss the probable causes of both problems.
5.5. DISCUSSION

5.5.2 Computation of $\theta_2$

It is unlikely that the dissipated power $q$, the measured temperature $T_h$ or the surface area $A_h$ encompass this problem because these values were controlled during the test setup. A different explanation is that the thermal resistance $\theta_2$ has been incorrectly approximated. Because the air layer between the hotspot and inside encasing is relatively thin, on average, measuring 2.5 mm, the conductive heat transfer through the inside air should be taken into account. If done, the following improvement will result:

$$L = \frac{W_e - W_h - 2 \cdot \text{thickness}}{2} = \frac{44 - 35 - 4}{2} = 2.5 \text{mm}$$

$$h_k = \frac{k_{air}}{L} = \frac{24 \cdot 10^{-3}}{2.5 \cdot 10^{-3}} = 9.6 \text{W/m}^2 \text{K}$$

$$T_h - T_i = q \cdot R_2 = q \cdot \frac{1}{(6, 87 + 6, 72 + 9, 60) \cdot 0.006} = 7.19 \text{K}$$

These calculations include the heat transfer coefficient of conduction, $h_k$, with the inside air results in $\Delta T$ of 7.98 K. This comes far closer to the measured temperature difference of (5, 20 K), compared to 12.78 K, derived from previous calculations. Therefore, for this product, air conduction inside the product plays a significant role in determining the temperature difference between the encasing and the hotspot when air layers are 2.5 mm. Further exploration is advised and should take into account more details of the hotspot and the encasing when calculating heat transfer coefficients and thermal resistance.

5.5.3 Computation of $\theta_4$

As can be seen in figure 5.4, the temperature is not evenly distributed across the surface of the encasing. A temperature difference $\Delta T$ of 13.5°C between the lowest and highest temperatures is measured. If the $\Delta T$ between the maximum temperature and the average temperature is calculated, the following results are reached: 38,0°C – 31,25°C = 6.75°C. It is likely that because only one thermocouple was used, a higher than average temperature was measured on one hand, while the average temperature was calculated on the other. The differences between measured and calculated temperatures are 12,20°C – 5.80°C = 6.40°C, which comes close to $\Delta T$ between the maximum and average temperatures.

Section 5.5.1 concludes that $\theta_4$ is computed with a too low factor of 0.48, resulting in a low estimation of the temperature difference $T_e - T_a$. One option for correcting this factor includes increasing the total heat transfer coefficient. This, however, would be a very unrealistic assumption. It is unlikely that the convection and radiation heat transfer coefficients, $h_c$ (equation 5.4.1) and $h_r$ (equation 5.4.2), have been estimated low. The heat transfer coefficient for convection has been estimated using an correlation for the Nusselt number of a vertical plate [54]. This correlation already results in a relatively high convection coefficient. In addition, the radiation heat transfer coefficient also has been calculated relatively high because a maximum emissivity $\epsilon = 1$ and maximum view
factor $F_{1,2} = 1$ have been used. The previous section discussed how conduction plays a significant role in calculating $\theta_2$ because of a thin air layer between the hotspot surface and the inside encasing surface. It is unlikely that this has a significant influence over the calculation of $\theta_4$, since the air on the outside of the product can move freely from the encasing surface to an ambient environment. A comprehensive elaboration is given in Teerstra’s article on natural convection in electronic enclosures [63].

Assuming that heat dissipation $q$ and the area of heat transfer $A_h$ have been correctly controlled in measurement calculations, the only option remaining is the deviation of temperatures on the encasing surface with regards to the average temperature, which is also calculated using the proposed model. Infrared measurements (figure 5.4) indicate that temperatures of the encasing are difficult to predict in detail. The difference between computations and measurements $12.2K - 5.8K = 6.4K$ is of the same magnitude as differences measured in values $6.75K$. The model thus predicts the average temperature of the encasing, but cannot predict local temperatures.

$t_{98\%}$ does not vary between various levels of power dissipation in the model. The temperature development in the model is exactly the same for both rates of dissipation, 1W and 2W, namely 4500 seconds. However, measurements indicate that, in reality, there is a significant difference between the measured value of $t_{98\%}$ (1W: 3840 seconds and 2W: 5280 seconds). This does not appear to be a result from a miscalculation of thermal capacitances $C_1$, $C_2$ and $C_3$ because it is a straightforward calculation. Therefore, it can be concluded that the proposed model does not take into account the effect of temperature on transient temperature prediction. This issue should be taken into account when undergoing follow-up research.

### 5.6 How to apply model 2 in design

The thermal RC-network presented in section 5.3 can be used to analyze transient temperature development in an electronic product during early design stages. The RC-network regards a product as something consisting of a single hotspot surrounded by the product encasing. It also takes into account the dimensions of the product and of the hotspot and relates this to the temperature of these elements.

On the basis of these equations, a software program can easily be developed that computes required parameters. The authors of this study have developed such a software program, named Theranizer, which numerically solves the system (figure 5.6). The model can now be easily applied to a given design by using the following requirements:

1. Gather the required design parameters.
2. Start the software program and fill in required variables.
3. Run the program.
4. Use the results to make design decisions and evaluate design changes.
5.7. CONCLUSIONS AND RECOMMENDATIONS

Figure 5.6: Numerical solver ‘Thermanizer’.

Figure 5.7 shows the results of ‘Thermanizer’. The absolute temperatures can be derived from these values by using proper addition. The temperature differences are described as follows:

- Core of the hotspot to hotspot encasing $T_c - T_h$.
- Hotspot encasing to inside encasing $T_h - T_i$.
- Inside encasing to outside encasing $T_i - T_e$.
- Outside encasing to the ambient environment $T_e - T_a$.

The present state of development for a software program is currently reliable enough for usability research, which is the main motivation for its development. It is recommended, if the application is successful, to extend the program using additional product configurations, including a valid area of application for each addition. Developing possibilities that would include use scenarios in order to improve transient analysis is also recommended.

5.7 Conclusions and recommendations

The approach presented in this study is useful for rough temperature estimation in an electronic product. The present results lead to the following conclusions: First, thermal
resistance between the hotspot and the encasing can be optimized by integrating conduction through the air inside the encasing. This results in a better approximation of $T_h - T_e$. Second, the model calculates the average temperature of the encasing within the targeted ±20%, but does not predict detailed maximum and minimum temperatures for the encasing. In addition, results show that average hotspot and encasing temperatures can be accurately estimated. The model predicts the value of $t_{98\%}$, with an accuracy of 17%. It is expected that integrating the temperature dependency of heat transfer coefficients for the model will improve the accuracy of the computed $t_{98\%}$. Future research should take this into account. In addition, there are large differences between the measured temperatures of the encasing. This is largely due to the high thermal resistance of the encasing material (plastic). Finally, the present study uses a very simple estimation for radiation, convection and conduction. Follow-up studies should take into account more details regarding dimensions (form-giving) and the effects of temperature on heat transfer coefficients.
This chapter describes the development and application of a formula for thermal design. The model is used in combination with temperature measurements for a functional model or a thermal mock-up during the beginning phases of the design process to evaluate different cooling concepts.
6.1 Introduction

Because designers of electronic products generally create a functional model (FUMO) or thermal mock-up to evaluate different cooling concepts, this chapter focuses on the following question: *Can a concept for formulas be developed that can be used in combination with measurements on a full-working model or thermal mock up?* The main idea here is to give the designer an easy-to-use formula applicable to conceptual design. The model is used to quickly evaluate cooling concepts by calibrating the model based on one measurement and exploring design changes by varying constants based on experience-values or estimations. The present study improves current practices by reducing the amount of time needed for measuring various design concepts by means of an FUMO or thermal mock-up.

This chapter begins by describing the approach. It begins with a section describing how the general equation is derived. The chapter continues with a section on measurements determined using thermocouples and an infrared camera. In order to evaluate the applicability of the model in different design configurations, a flexible measurement platform has been developed in which design options, such as encasing materials, open versus closed encasing and active versus passive cooling, can be varied. The section finishes with a description of how to reduce measurement time by applying a least square approximation algorithm on measurement data found in matlab. The result is a method with two benefits. The first benefit is an increase in efficiency (less time) in obtaining measurements because measurements do not have to be executed until steady-state. The second benefit is a more accurate approximation of the steady-state temperature and time constant than that obtained through visual curve fitting. The practical application of the models in design is then discussed and an example is given in which the method for practical application is applied on a measured mock-up system.

6.2 Approach of model 3

In the following sections, a mathematical model for temperature prediction in an electronic product will be derived. As a basis for the model, an electronic product will be viewed as if it were one single hotspot within an encasing. In reality, the hotspot could be a power-dissipating component, such as a coil, IC or the average temperature of a printed circuit board. Based on this abstraction, a mathematical model will be derived. The model can be used to describe the effect of design changes on hotspot temperature. Several design variables will be taken into account, including an open or closed encasing, passive cooling or active cooling and materials used for the encasing.
6.3. Model definition

In this section, a framework for evaluating various cooling concepts will be described. The framework is based on an RC-network, shown in figure 6.1. First, the variables in the RC-network will be described. Next, a mathematical model representing various cooling options will be derived. The objective of the model is to give insight into transient behaviors of the hotspot and encasing temperatures. There are several requirements

![Thermal resistor-capacitor network](image)

Figure 6.1: Thermal resistor-capacitor network.

In this paper, extended mathematical relations compared to previous studies of heat transfer will be discussed. Based on the insights gained through this analysis, the mathematical model can be expanded into something more complex. Several steps will be taken to derive the model and develop a method for practical application. The steps are as follows:

**Step 1: Model definition**  Description and general exploration of the equation. The model is a one-dimensional RC-network. However, this model uses only one thermal capacitance, making it possible to derive an equation. Numerical approximation becomes unnecessary.

**Step 2: Measurements**  An overview of the development of a flexible mock-up system and measurement results. The flexible mock-up system aims at evaluating whether or not the model can be used to predict changes in product configuration once the model has been calibrated for one of the proposed configurations. All configurations are measured with T-type thermocouples that have a tolerance of ±1°C. Infrared measurements have been executed to discuss the effects of encasing materials on the temperature distribution for the surface of the encasing.

**Step 3: Discussion**  Discussion on the results of the previous section.

**Step 4: Practical application**  A description of the practical use of the model in a design situation.

**Step 5: Conclusions and recommendations**  Conclusions drawn from the research as described in this chapter.
that the model must fulfill. The model must represent different cooling configurations (figure 6.2) and must predict hotspot and encasing temperatures.

6.3.1 Model description

As a precondition, only one hotspot will be taken into account. Future studies should explore the effects of additional hotspots on temperature development. The RC-network contains several variables that correspond to different aspects of temperature development in an electronic product. To begin with, there is the power dissipation \( q \) of the hotspot. The following variable is the thermal capacitance \( C \) of the device. In this model, the total thermal capacitance of a product will be derived, based on measurements.

In the thermal RC-network, there are several heat flows that must be taken into account. The source for the heat flow is \( q \). As a result of \( q \), the product begins to heat. This property is represented by heat \( q_1 \) into thermal capacitance \( C \). As a result of the heat flow in \( C \), the temperature of the product rises and heat flows to an ambient environment. The heat flow to the ambient environment can be divided in two flows. First, a possible forced or passively induced flow of air through the device via openings in the encasing may exist. This is represented by \( q_2 \). Second, a flow of heat in the form of natural convection and radiation through the encasing \( q_3 \) may also be present.

There are several thermal resistances that determine power flows and temperature distribution within a system. First, a thermal resistance models heat transfer through a flow of air through the product \( \theta_1 \). This can occur through either natural or forced convection. For fully closed encasings, the value of this thermal resistance will be set to an infinite value of \( \infty \). Second, the model contains two thermal resistances that describe the heat flow \( q_3 \) through the encasing. This include heat flow from the hotspot to the exterior of the encasing \( \theta_2 \) and heat flow from the exterior of the encasing to an ambient environment \( \theta_3 \). These thermal resistances are derived from measurements from a mock-up system.

The result of these described thermal resistances and heat flows of a product within a specific ambient temperature \( T_a \) is a hotspot temperature of \( T_h \) and an average encasing exterior temperature of \( T_e \).

6.3.2 Exploring the general equation

Based on the thermal network, equations for temperature development can be derived. The resulting differential equation is used to calculate transient temperature behavior (equation 6.3.8) and predict design changes based on a standard mock-up configuration. A description of the heat flow balance in the system is given in the following:

\[
q = q_1 + q_2 + q_3
\]  

(6.3.1)

The total thermal resistance from hotspot to ambient environment can be derived as the following:
6.3. MODEL DEFINITION

\[ \theta = \frac{\theta_1 (\theta_2 + \theta_3)}{\theta_1 + \theta_2 + \theta_3} \]  \hspace{1cm} (6.3.2)

The heat flow equation can now be more specific. First, \( q_1 \) can be calculated by multiplying the thermal capacitance \( (C = mc_p) \) with the hotspot temperature/time differential \( \frac{dT_h}{dt} \).

\[ q_1 = mc_p \frac{dT_h}{dt} \]  \hspace{1cm} (6.3.3)

Next, \( q_2 + q_3 \) can be defined by dividing the temperature difference from the hotspot to an ambient environment \( (T_h(t) - T_a) \) with the total thermal resistance \( \theta \).

\[ q_2 + q_3 = \frac{T_h(t) - T_a}{\theta} \]  \hspace{1cm} (6.3.4)

Heat flow balance can now be defined and solved using \( \frac{dT_h}{dt} \) in order to obtain the following differential equation:

\[ q = mc_p \frac{dT_h}{dt} + \frac{T_h(t) - T_a}{\theta} \Leftrightarrow \frac{dT_h}{dt} = \frac{q - \left( \frac{T_h(t) - T_a}{\theta} \right)}{mc_p} \]  \hspace{1cm} (6.3.5)

In order to solve this differential equation, the values are at steady-state, at which state it is known that the heat flow \( q_1 \) into the thermal capacitance \( C \) is zero and the temperature of the hotspot is maximum and constant \( T_{hm} \). This should be defined as the following:

\[ q = \frac{T_{hm} - T_a}{\theta} \]  \hspace{1cm} (6.3.6)

Figure 6.2: Several mock-up configurations.

\[ T_{hm} = \frac{T_h(t) - T_a}{\theta} \]  \hspace{1cm} (6.3.7)
This condition can then be combined with the differential equation, resulting in the following:

\[
\frac{dT_h}{dt} = q - \frac{(T_{hm} - T_a)}{C} \quad (6.3.7)
\]

Integrating the previous equation results in the following equation:

\[
T_h(t) = T_{hm} - e^{\left(\frac{t}{\theta_1}\right)}(T_{hm} - T_a) \quad (6.3.8)
\]

The equation can be further developed in order to find equations that describe the temperature development of the hotspot \(T_h(t)\) and the encasing \(T_e(t)\) in relation to \(\theta_1\), \(\theta_2\) and \(\theta_3\):

\[
T_{hm} - T_a = q_2 \cdot \theta_1 = q_3 \cdot (\theta_2 + \theta_3) = q \cdot \frac{\theta_1(\theta_2 + \theta_3)}{\theta_1 + \theta_2 + \theta_3} \Rightarrow
\]

\[
q_2 = q \cdot \frac{\theta_1 + \theta_3}{\theta_1 + \theta_2 + \theta_3}
\]

\[
q_3 = q \cdot \frac{\theta_2 + \theta_3}{\theta_1 + \theta_2 + \theta_3}
\]

From the general equation \(T(t) = T_{hm} - e^{\frac{t}{\theta_1}}(T_{hm} - T_a)\), two equations can be derived for \(T_h(t)\) and \(T_e(t)\):

\[
\begin{align*}
T_h(t) &= T_{hm} - e^{\frac{t}{\theta_1}}(T_{hm} - T_a) \\
T_h(t) &= q \cdot \frac{\theta_1(\theta_2 + \theta_3)}{\theta_1 + \theta_2 + \theta_3} + T_a - e^{\frac{t}{\theta_1}}(q \cdot \frac{\theta_1(\theta_2 + \theta_3)}{\theta_1 + \theta_2 + \theta_3}) \\
T_e(t) &= T_{em} - e^{\frac{t}{\theta_1}}(T_{em} - T_a) \\
T_e(t) &= q \cdot \frac{\theta_1(\theta_1 + \theta_3)}{\theta_1 + \theta_2 + \theta_3} + T_a - e^{\frac{t}{\theta_1}}(q \cdot \frac{\theta_1^2 + \theta_3}{\theta_1 + \theta_2 + \theta_3})
\end{align*}
\]

From these two functions, a matrix equation can be derived that defines the whole system of equations. The matrix equation may be expanded when the complexity of the resistance network is increased. The matrix equation is as follows:

\[
\begin{bmatrix}
T_h(t) \\
T_e(t)
\end{bmatrix} =
\begin{bmatrix}
T_a \\
T_a
\end{bmatrix} +
\begin{bmatrix}
\frac{\theta_1(\theta_2 + \theta_3)}{\theta_1 + \theta_2 + \theta_3} & \frac{\theta_1(\theta_1 + \theta_3)}{\theta_1 + \theta_2 + \theta_3} \\
\frac{\theta_1 + \theta_2 + \theta_3}{\theta_1 + \theta_2 + \theta_3} & \frac{\theta_1 + \theta_2 + \theta_3}{\theta_1 + \theta_2 + \theta_3}
\end{bmatrix}
\cdot
\begin{bmatrix}
q \\
-q \cdot e^{\frac{t}{\theta_1}}
\end{bmatrix} \quad (6.3.9)
\]

For a closed encasing, the value of \(\theta_1\) can be defined as infinite. If the matrix equation is solved, the values for \(\theta_2\) and \(\theta_3\) can be derived by measuring a mock-up in a closed configuration. For this situation, the following can be derived:

\[
\begin{align*}
\lim_{\theta_1 \to \infty} q_2 &= \lim_{\theta_1 \to \infty} q \cdot \frac{\theta_1 + \theta_3}{\theta_1 + \theta_2 + \theta_3} = 0 \\
\lim_{\theta_1 \to \infty} q_3 &= \lim_{\theta_1 \to \infty} q \cdot \frac{\theta_2 + \theta_3}{\theta_1 + \theta_2 + \theta_3} = q \\
T_{hm} &= q \cdot (\theta_2 + \theta_3) \\
T_{em} &= q \cdot (\theta_3)
\end{align*}
\]

The result is the following matrix equation:

\[
\begin{bmatrix}
T_h(t) \\
T_e(t)
\end{bmatrix} =
\begin{bmatrix}
T_a \\
T_a
\end{bmatrix} +
\begin{bmatrix}
\theta_2 + \theta_3 & \theta_2 + \theta_3 \\
\theta_3 & \theta_3
\end{bmatrix}
\cdot
\begin{bmatrix}
q \\
-q \cdot e^{\frac{t}{\theta_1}}
\end{bmatrix} \quad (6.3.10)
\]
Based on equation 6.3.8, temperature estimates for the encasing and other parts of the device can be executed through breaking down the total thermal resistance (figure 6.1). Equation 6.3.9 is now ready for calibration and exploration in the following sections of this chapter.

6.4  Thermocouple measurements

In this section, the results of the thermocouple measurements will be presented. There are several reasons for obtaining the present measurements. First, the measurements are needed to obtain more insight into heat transfer and the distribution of temperature within a mock-up. Second, measurements give insight into differences for possible cooling configurations. Third, the measurements will be used at the end of this chapter to compare predictions with a calibrated model and evaluate the predictability and accuracy of the model.

Because the intention is to obtain insight into the effects of design changes, these measurements will cover different configurations previously described (see figure 6.2).
A mock-up is a device that contains one hotspot, in this case, a piece of copper with a resistor inside. Many of these design options can be varied, as is shown in the following:

- The encasing material can be changed (polystyrene and aluminium).
- The encasing can be either closed or open.
- The airflow can be changed from natural convection to forced convection by integrating a small fan.
- The surface area of the hotspot can be increased (cooling fins).

### 6.4.1 Method

The temperature of each set-up has been measured by means of a data logger. All temperatures are logged once each minute until a steady-state situation has been reached. Temperature measurements have been achieved within a laboratory environment, using an ambient temperature $T_a$ that varied by $\pm 2^\circ C$ around an ambient temperature of approximately $23^\circ C$. The fluctuations in ambient temperature fall within a reasonable range. To interpret the data, temperature differences are used. This is a convenient method for correcting fluctuations in ambient temperature. T-type thermocouples have been attached to the hotspot and the top, bottom, front, back, left and right of the encasing. The reference temperature has been attached to the tripod that holds the mock-up. Figure 6.3 gives an overview of the measurement set-up and the components used to build the different configurations.

Each configuration has been tested for at least three different ranges of power dissipation. The ranges were chosen in such a way that the level of maximum power delivers a hotspot temperature between $60^\circ C$ and $70^\circ C$. This temperature limit results from achieving the maximum allowed temperature for the material used in the mock-up (polystyrene). A total of 38 measurements have been executed. The aim of the present study is to discuss the predictability of equation 6.3.9. The derivation of constants based on the measurements is supported by the use of an unconstrained minimization algorithm in matlab in combination with the measured data (appendix C). The result is a proper approximation of the steady-state temperature and the time constant.

### 6.4.2 Results and discussion

In this section, the results of the measurements are presented and discussed. The section is divided into several subsections. First, the steady-state temperature difference between hotspot and ambient temperatures is described. Second, the steady-state temperature difference between average encasing and ambient temperatures is evaluated. This is followed with a discussion about the difference between average encasing and maximum encasing temperatures. The time constants of the transient behavior are then discussed. Finally, thermal resistance and capacitances are derived for all measurements.
6.4. THERMOCOUPLE MEASUREMENTS

Steady-state temperature differences

This section discusses temperature differences between the hotspot and ambient environment, or $\Delta T = T_h - T_a$ (figure 6.4) and between the average encasing and ambient environment $\Delta T = T_e - T_a$ (figure 6.5). The average encasing temperature is derived from measurements taken from the top, bottom, front, back, left and right of the encasing.

For configuration A, $T_h$ is higher with aluminium than with polystyrene. For all other configurations, however, this is not the case. It could be suggested that in the case of configuration A, the emissivity of the encasing material plays a significant role. The emissivity of white plastic is between 0.84-0.95 [28] and the emissivity of polished aluminium is between 0.04-0.06 [24], which should result in a large difference in heat transfer coefficients between the two materials. Radiation is a complex phenomenon. It would not be appropriate to conclude more than the above suggestions based solely on thermocouple measurements. Figure 6.4 shows that for the thermal mock-up presented here, the encasing material influences hotspot temperature. Implementing an encasing material with a high level of conductivity (aluminium) will result in lower hotspot temperatures, because heat can spread more easily throughout the material. This effect is highly noticed in the case of configuration E, where the hotspot is attached to the encasing. For a power dissipation of 1.0W, the $\Delta T$ of aluminium is 50% of the $\Delta T$ of polystyrene.

Comparing configuration C with configuration B in figure 6.4 leads to the suggestion that, for open encasings, extending the cooling surface by means of cooling fins results in a lower hotspot temperature. Figure 6.5 shows, however, that this is not necessarily the case for an average encasing temperature. Figure 6.4 and figure 6.5 suggest that a ventilated product, by means of forced convection, significantly reduces both $T_h$ and $T_e$. For configuration F, which is unvented but uses forced convection inside, an approximate 50% reduction in hotspot temperature, with regards to configuration A and B, is observed. In most cases, thermal resistance is higher at low power dissipations. This suggests that the effect is related to non-linear behavior of the heat transfer coefficient. For configurations A,B,C,D and F, the effects of changing encasing materials are relatively small. Configuration E (the hotspot is attached to the encasing) indicates a significant differ-
Figure 6.5: Temperature differences for the average encasing to an ambient environment.

ence between using polystyrene and aluminium as an encasing material. For both cases presented in configuration C, a clear reduction in hotspot temperature by enlarging the cooling surface (cooling fins) is realized. In general, the hotspot temperature is lower when an aluminium encasing is used, and by adding a fan, the set-up could dissipate a significantly higher amount of power, resulting in a factor of approximately seven times the power dissipation, compared to the average hotspot temperature. With configuration E, the effects on hotspot temperature are very large in both cases, with a 30% to 70% improvement. Configuration F shows that internal air circulation can reduce hotspot temperature by approximately 50%, compared to configuration A.

Comparison of maximum and average encasing temperatures

This paragraph will discuss differences between maximum measured encasing and average measured encasing temperatures. For configurations A and F, there is generally little difference between maximum encasing and average encasing temperatures. Configurations C, D and E show a large difference between maximum encasing temperature and average encasing temperature. There is a noticeably large difference between aluminium and polystyrene. Aluminium, with its higher thermal conductivity, better distributes heat and reduces differences between average and maximum encasing temperatures. By far, configuration E gives the highest rate between maximum and average encasing temperatures, which is likely due to the fact that the hotspot has been attached to the encasing.

Evaluation of time constants

Time constants derived using the function for unconstrained minimization, given in appendix C, are presented in table 6.1. Time constants derived using data from temperature measurements for the hotspot appear relatively consistent per configuration. One that significantly differs is Al-E-0.25. This deviation is a result of high fluctuations in temperature measurements during start-up.
Table 6.1: Time constants $X = \theta \cdot C$ in seconds.

### 6.4. THERMOCOUPLE MEASUREMENTS

#### Derivation of total thermal resistance and capacitance

The total thermal resistance and capacitance of equation 6.3.8 can be derived from measurements. In the case of a single hotspot, the total thermal resistance can be derived using equation 6.3.2. The total thermal resistance $\theta$ is calculated by dividing the temperature difference $\Delta T = T_h - T_a$ with the dissipated power $q$. Thermal capacitance $C$ can then be derived from the quotient of the time constant $X$ and $\theta$: $C = \frac{X}{\theta}$.

The derived results of the thermal resistance and capacitance for the twelve different configurations are displayed in table 6.2 and table 6.3. Thermal resistance values and capacitance appear to be relatively consistent per configuration. Thermal resistance significantly decreases in configuration D, where a fan was used. The large difference between thermal resistance values for polystyrene configuration E and aluminium configuration E explains the positive effect of heat spread by using a material with high levels of thermal conductivity, compared to a material with low levels of thermal conductivity.

Configurations A and B have approximately the same thermal capacitance. However, the amount in configuration B is slightly less because some material has been removed...
from the top and bottom of the encasing. In configuration C, cooling fins have been added. These are made of aluminium and therefore result in a higher level of thermal capacitance. In configuration D, a small fan has been added in addition to the cooling fins. This, again, results in an increase of thermal capacitance. Configuration E has one value for the aluminium encasing that is significantly different from the other values. This is most likely caused from derivations in the measurements (see figure 6.1). Configuration F shows a large difference between derived thermal capacitances. The cause for this is presently unclear.

Table 6.2: Thermal resistance $\theta$ [K/W]

<table>
<thead>
<tr>
<th>Config.</th>
<th>0.25W</th>
<th>0.5W</th>
<th>1.0W</th>
<th>2.0W</th>
<th>5.0W</th>
<th>7.5W</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS A</td>
<td>40</td>
<td>38</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al A</td>
<td>42</td>
<td>40</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS B</td>
<td>39</td>
<td>36</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al B</td>
<td>36</td>
<td>33</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS C</td>
<td>26</td>
<td>23</td>
<td>21</td>
<td>22</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Al C</td>
<td>23</td>
<td>22</td>
<td>20</td>
<td>21</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>PS D</td>
<td></td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Al D</td>
<td></td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>PS E</td>
<td>27</td>
<td>24</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al E</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS F</td>
<td>21</td>
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<td>15</td>
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<td></td>
</tr>
<tr>
<td>Al F</td>
<td>18</td>
<td>15</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Thermal capacitance $C$ [J/K]

<table>
<thead>
<tr>
<th>Config.</th>
<th>0.25W</th>
<th>0.5W</th>
<th>1.0W</th>
<th>2.0W</th>
<th>5.0W</th>
<th>7.5W</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS A</td>
<td>19</td>
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<td>22</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Al A</td>
<td>18</td>
<td>21</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS B</td>
<td>15</td>
<td>20</td>
<td>20</td>
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<td></td>
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</tr>
<tr>
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<td>18</td>
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<td></td>
</tr>
<tr>
<td>PS C</td>
<td>34</td>
<td>38</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al C</td>
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<td>34</td>
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<td></td>
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<td>56</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Al D</td>
<td></td>
<td>42</td>
<td>42</td>
<td>58</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
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<tr>
<td>PS F</td>
<td>23</td>
<td>26</td>
<td>41</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al F</td>
<td>26</td>
<td>35</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.5 Infrared thermography measurements

In this section, the results of infrared thermography measurements will be presented. There are two goals for these measurements. First, the measurements are needed to obtain more insight in the distribution of temperature on the surface of the encasing.
Second, the measurements are an addition to thermocouple measurements described in the previous section.

6.5. Method

The same mock-up system is used as was used in previously described temperature measurements. The emissivity of materials in the mock-up system is not similar, especially differences between polystyrene and polished aluminium (see section 6.4.2). In order to obtain comparable results, the device has been uniformly colored with hydrated magnesium silicate powder (talc powder), shown on the left side of figure 6.7 to determine uniform emissivity of different materials used. However, applying a coating on the surface of the aluminium encasing does influence heat transfer through radiation due to changes in emissivity.

This mock-up has been modified with one transparent side (figure 6.7), enabling individuals to see inside the device. This was also included to keep temperature distribution as realistic as possible (especially for configuration A) by preventing ventilation through the product. Two different configurations, namely closed and open encasings, respectively A and B, have been analyzed using infrared measurements. The two materials tested include polystyrene and aluminium.

6.5.2 Results and discussion

Figure 6.7 shows results for four experiments. The experiments encompass both configurations A and B (closed and open encasings), using both polystyrene and aluminium encasing material. The results show the influence encasing material has on temperature
distribution along the encasing surface and the reduction in hotspot temperature experienced by ventilation. Ambient temperature $T_a$ and hotspot temperature $T_h$ have been obtained using measurements determined by means of software, which is compatible with the infrared thermography camera, ThermaCAM Researcher$^\text{TM}$[62]. The results are given in table 6.4.

<table>
<thead>
<tr>
<th>Config.</th>
<th>$T_a$ [$^\circ$C]</th>
<th>$T_h$ [$^\circ$C]</th>
<th>$T_h - T_a$ [$^\circ$C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS A</td>
<td>21</td>
<td>34</td>
<td>13</td>
</tr>
<tr>
<td>PS B</td>
<td>20</td>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>Al A</td>
<td>21</td>
<td>33</td>
<td>12</td>
</tr>
<tr>
<td>Al B</td>
<td>18</td>
<td>27</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 6.4: Infrared results.

An encasing with a higher level of thermal conductivity shows a lower hotspot temperature, in this case, $T_h = 12^\circ$C for aluminium versus $13^\circ$C for polystyrene with configuration A and $12^\circ$C versus $9^\circ$C for configuration B. Ventilation holes appear to have an improved effect on the hotspot temperature for this mock-up system. From figure 6.8, which shows a 3D view of aluminium and polystyrene in configuration B, a more even distribution of temperature across the encasing surface, compared to polystyrene, can be noticed.

### 6.6 How to apply model 3 to a design

In this section, a description will be given of the practical use of the mathematical model (equation 6.3.8) as a standard formula in the design of an electronic product. The method will be presented as a stepwise plan which is easy to understand and should be applied as follows:

1. Measure the hotspot temperature, average encasing temperature and the ambient temperature every minute until the temperature has reached an approximate steady-state. Also, measure the amount of dissipated power coming from the device. It
is advisable to choose dissipated power such that the temperature of the hotspot reaches its approximate maximum allowable value.

2. Derive the steady state temperature and time constant $X$ from the measurements. $X = \theta C$ occurs at approximately the same time as when the temperature of the hotspot reaches 63% of its steady-state value.

3. Derive the thermal resistance and thermal capacitance using the following equations: $\theta = \frac{T_{hm} - T_a}{q}$ and $C = \frac{X}{\theta}$

4. Use the $\theta$ and $C$ values to calibrate the general equation $T_e(t) = T_{hm} - e^{\theta t}(T_{hm} - T_a)$. Set up the matrix equations to calculate hotspot and encasing temperatures.

5. Use the equation to study design changes.

6.6.1 Example

In this section, model 3 and its method for application will be applied to the variable mock-up system described in this chapter. The model will be first calibrated using results from the measurements shown in configuration A, which was executed using polystyrene with a 0.5W power dissipation. Then, the calibrated model will be used to predict the effects of design changes on configurations A, B, C, D, E and F, with 1W power dissipation. These results will be compared to the measurement data.

![Figure 6.9: Comparison of measurements and predictions for configuration A with a 0.5W power dissipation.](image)

**Step 1:** In a mock-up for a design, measure the hotspot, average encasing and ambient temperatures.

Measurements are presented for $T_h$, $T_e$ and $T_a$. Configuration A uses polystyrene material for the encasing and sets the calibration at 0.5W. For power dissipation, see fig-
Step 2: Derive the steady-state temperature and time constant \(X\) from the measurements.

The time constant for this configuration has been derived in section 6.4.2 and is given in table 6.1: \(X = 746 \text{ [s]}\)

Step 3: Derive the thermal resistance.

The following values for \(\theta\) and \(C\) have been derived in section 6.4.2 and are given in table 6.2 and table 6.3: \(\theta = 38 \text{ [K/W]}\) and \(C = 20 \text{ [J/K]}\). The following measurement for thermal resistance \(\theta_3\) is derived from the average steady-state encasing temperature (figure 6.5): \(\theta_3 = (T_e - T_a)/q = 10 \text{ [K/W]}\). The following measurement for thermal resistance inside the configuration \(\theta_2\) results from differences between \(\theta\) and \(\theta_3\): \(\theta_2 = \theta - \theta_3 = 28 \text{ [K/W]}\). Finally, the following thermal resistance \(\theta_1\) will be set to equal infinity, since the model is calibrated for a fully closed encasing, \(\theta_1 = \infty \text{ [K/W]}\).

Step 4: Calibrate the general equation.

The results of the calibrated model are shown in figure 6.9. Since the model is calibrated for a fully closed encasing, the following matrix equation is used:

\[
\begin{bmatrix}
T_h(t) \\
T_e(t)
\end{bmatrix} = \begin{bmatrix}
T_a \\
T_a
\end{bmatrix} + \begin{bmatrix}
\theta_2 + \theta_3 & \theta_2 + \theta_3 \\
\theta_3 & \theta_3
\end{bmatrix} \cdot \begin{bmatrix}
q \\
-q \cdot e^{-\theta_3}
\end{bmatrix}
\]

Step 5

Based on the calibrated model, predictions are made for all configurations with a power dissipation of 1,0W. Results are compared to measurements for a polystyrene encasing and given in figure 6.10. A summary of the variables and values used in the predictions is given in table 6.5. The predictions have been completed using the following assumptions:

**PSA\textsubscript{1,0}** Predicted by changing levels of power dissipation \(q\) to 1,0W.

<table>
<thead>
<tr>
<th>Var.</th>
<th>PSA\textsubscript{0.5}</th>
<th>PSA\textsubscript{1.0}</th>
<th>PSB\textsubscript{1.0}</th>
<th>PSC\textsubscript{1.0}</th>
<th>PSD\textsubscript{1.0}</th>
<th>PSE\textsubscript{1.0}</th>
<th>PSF\textsubscript{1.0}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x) [s]</td>
<td>746</td>
<td>746</td>
<td>597</td>
<td>355</td>
<td>61</td>
<td>206</td>
<td>256</td>
</tr>
<tr>
<td>(q) [W]</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(\theta) [K/W]</td>
<td>38</td>
<td>38</td>
<td>30</td>
<td>18</td>
<td>3</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>(\theta_1) [K/W]</td>
<td>(\infty)</td>
<td>(\infty)</td>
<td>139</td>
<td>33</td>
<td>3</td>
<td>(\infty)</td>
<td>(\infty)</td>
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<tr>
<td>(\theta_2) [K/W]</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>(\theta_3) [K/W]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>(C) [J/K]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
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</tbody>
</table>

Table 6.5: Variables and values used in predictions.
6.6. **HOW TO APPLY MODEL 3 TO A DESIGN**

Figure 6.10: Comparison of measurements and predictions for configuration A, B, C, D, E and F.

**PSB1.0** In this prediction, $\theta_1$ thermal resistance is added because the configuration is open and dissipation to the ambient environment must be taken into account. $\theta_1$ is estimated by taking into account the top area $A = 2 \cdot 4 \cdot 10^{-2} \cdot 3 \cdot 10^{-2} = 7, 2 \cdot 10^{-4}$ [m$^2$] of the hotspot and the heat transfer coefficient $h_c = 10$ [W/m$^2$K]: $\theta_1 = \frac{1}{h_c \cdot A} = 139$ [K/W].

**PSC1.0** For these predictions, $\theta_1$ thermal resistance is added because the configuration is open and dissipation to the ambient environment must be taken into account. In this configuration, five cooling fins have been added. $\theta_1$ is estimated using the surface area of the cooling fins $A = 2 \cdot 5 \cdot 1 \cdot 10^{-2} \cdot 3 \cdot 10^{-2} = 3 \cdot 10^{-3}$ [m$^2$] and $h_c=10$ [W/m$^2$K]. This results in a thermal resistance of $\theta_1 = 1/(h_c \cdot A) = 33$ [K/W].
For the following predictions, $\theta_1$ thermal resistance is added because the configuration is open and dissipation to the ambient environment must be taken into account. Cooling fins are attached to the hotspot. $\theta_1$ is therefore estimated as having an area of $A = 2 \cdot 5 \cdot 1 \cdot 10^{-2} \cdot 3 \cdot 10^{-2} = 3 \cdot 10^{-3} \text{[m}^2\text{]}$. For forced convection, a heat transfer coefficient $h_c = 100 \text{[W/m}^2\text{K]}$ is proposed. The results for thermal resistance are $\theta_1 = \frac{1}{h_cA} = 3 \text{[K/W]}$.

For predictions, the $\theta_2$ thermal resistance is changed because the hotspot is attached to the encasing. Between the hotspot and encasing a thermal conductive foil has been used with a thermal conductivity of $k = 0,9 \text{[W/mK]}$ and a thickness of $x = 0,2 \cdot 10^{-3} \text{[m]}$. The surface area is the same as in configuration PSB, $A = 2,4 \cdot 10^{-2} \cdot 3 \cdot 10^{-2} = 7,2 \cdot 10^{-4} \text{[m}^2\text{]}$, which results in thermal resistance $\theta_2 = \frac{x}{kA} = 0,3 \approx 0 \text{[K/W]}$.

These predictions incorporate changes in $\theta_2$ because a fan is added inside the mock-up. A forced convection heat transfer coefficient of $100 \text{[W/m}^2\text{K]}$ is therefore proposed. This results in a thermal resistance of $\theta_2 = 2,8 \approx 3 \text{[K/W]}$, which is ten times smaller than those proposed in configuration A.

### 6.7 Interpretation and conclusion

A model has been developed that determines hotspot and encasing temperatures in an electronic device based on measurements gained through a full working model or thermal mock-up. The model can be used to predict the effects of changes in power dissipation or configurated temperatures. Figure 6.10 gives insight into the quality of predicted temperature behavior by manipulating parameters within the model. Very basic changes have been proposed that only encompass the manipulation of thermal resistance within the model. The results show that for configurations A, B, D and F, the predictions give a reasonable indication of the magnitude of the effects of design changes. However, for configurations C and E, the result is not satisfactory. For configuration C, the time constant is estimated too low. For configuration E, the steady-state temperatures significantly deviate from measured temperatures. In summary, it is advised that caution be taken when executing rough predictions, such as those presented here. In addition, the generality of applying the method described here with design specialists in the field should be discussed. The present model is a basis for further exploration and application in a usability study. However, future research should proceed by evaluating the predictability of calibrated models in other examples and design studies.
In this chapter, the applicability, efficiency and quality of the models and methods that were described in previous chapters will be evaluated. This will be done by means of a usability experiment.
CHAPTER 7. EVALUATION THROUGH EXPERIMENTS

7.1 Introduction

In this chapter, the following question is discussed: What is the applicability, efficiency and quality of the models? This is done by completing a usability experiment. A key aspect for completing this is the background of the participants. Most designers appeared to have little ready-to-apply knowledge on heat transfer, which made the instant application of models difficult. Therefore, this process was begun by educating the participants who were novice designers about the models. Afterwards, the participants applied the models to a design assignment. Observing this process gave insight into the applicability, efficiency and quality of the models.

7.2 Goal

The aim of this project is to support thermal analysis during the conceptual phase of electronic product design. It has been suggested that by supporting practical problems in the field, the general research question, How can the thermal design of electronic products be optimized in the conceptual phase of product development?, can be answered. Models and methods have been developed to support three problems that appeared during the literature study (chapter 2) and expert interviews (chapter 3):

1. Designers are unfamiliar with heat transfer theory and thermal design theory → model 1.

2. Evaluation of structural concepts on temperature development is not supported by a standard approach → model 2.

3. Temperature measurements on mock-ups and functional models are time-consuming, but crucial to thermal design → model 3.

In this chapter, models and methods will be evaluated to determine whether or not they support the problems described above. It has been proposed that by developing three models that focus on these three problems, the design process can be optimized. This project proposes that the design process will become optimized when these models are applicable, efficient and result in better quality products. Therefore, the following evaluative questions are proposed:

Research question I Are the presented methods applicable to designers?

Research question II Does application of the present models improve the efficiency of the design process for electronic equipment?

Research question III Does application of the present models increase the quality of electronic product designs?
7.3 Pilot study

To obtain experience similar to how designers at the present time execute temperature estimations, a pilot experiment has been conducted. The experiment explores the approach of designers when estimating temperatures in a design assignment and to what extent participants are able to find heat transfer variables needed to evaluate a thermal design. The pilot study began with a preliminary interview to assess participants’ levels of experience with heat transfer. The preliminary interview indicates that three of the four participants have a background in heat transfer. Only one participant actually had experience with the design of electronic products where thermal problems arose or in which temperature was a critical design issue. The participants have different backgrounds in mechanical, design and aerospace engineering.

In the assignment, participants were asked to design the encasing for a small AC-DC adapter. The electronic contents of the adapter were given (figure 7.1). The assignments had to be completed within 30 minutes. The designers were given constraints for the design: a maximum hotspot surface temperature of 70°C and maximum encasing dimensions of 60mm × 60mm × 60mm. The power dissipation was given as 4W, which should have resulted in the conclusion that the product should be actively cooled. In order to obtain results that reflect most closely to the practice of the participants, the assignment took place in participants’ offices. Participants were asked to design an AC-DC adaptor and were allowed to use all available means, including handbooks or computer software, to complete the task. In addition, two handbooks that contain basic information with regards to heat transfer were given to participants. Participants were asked to speak out loud throughout the experiment. During the study, notes were taken in order to describe some of the steps and tasks that participants undertook when coming to a solution. The notes have also been used to discuss to which extent participants derive heat transfer variables used in heat transfer calculations.

In general, all participants drew some kind of scheme and managed to find some primary modes of heat transfer, convection, radiation and conduction. What encasing material was used and its relationship with the thermal capacitance of the device was also recognized. However, none of the participants managed to develop a thermal model by means of a resistor or resistor-capacitor network, let alone succeed in calculating the actual hotspot temperature. Consequently, the conclusion is reached that it is not
possible to compare models 1-3 with participants’ own methods because they could not obtain a comparable result. It is therefore necessary to “educate” participants about the basic heat transfer theory and give them a standard tool in order to compare models with their current levels of knowledge. In this experiment, a method has been used where participants are taught a standard method, the resistor network theory, in addition to models 1-3.

### 7.4 Experiment design

An experiment design has been set up to evaluate the applicability, efficiency and quality of the three models and methods. The research protocol is given in appendix D. Seven novice designers, master students from the school of design engineering at Delft University of Technology, participated in the experiment. Novice designers are used because of the limited time available to select participants. It is advisable to allow more time for selection so that experienced participants may be included in subsequent studies. Six of the participants have a background in industrial design engineering and one has a background in aerospace engineering. A preliminary questionnaire was distributed to assess the experience of participants with heat transfer and thermal design. Table 7.1 presents an overview of the results.

Although some of the participants indicated a familiarity with heat development in products, they appeared generally unexperienced in the field. Several participants have a background in heat transfer. Specifically, Participant 6 has teaching experience in thermodynamics. None of the respondents have experience using computational fluid dynamics (CFD) or finite element analysis (FEA) in relation to temperature analysis. Although several participants indicate having a background in heat transfer, none of the respondents indicate that they would use standard approaches, such as resistor capacitor networks, CFD or FEA, to calculate temperatures.

Before the experiment took place, participants received an email, which contained an overview of the models and methods for practical application. In the present case, four models have been presented. Model 0 includes a general description of how to apply resistor-network theory and models 1, 2 and 3, which are the models described in chapters 4, 5 and 6. During the experiment, participants were given advise on how to

<table>
<thead>
<tr>
<th>Participant</th>
<th>Type</th>
<th>Heat Tr. backgr.</th>
<th>used CDF/FEA</th>
<th>Th.Des. exp.</th>
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<td>P01</td>
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<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>P02</td>
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<td>no</td>
<td>no</td>
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<tr>
<td>P03</td>
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<td>yes</td>
</tr>
<tr>
<td>P04</td>
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<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>P05</td>
<td>novice</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>P06</td>
<td>novice</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>P07</td>
<td>novice</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 7.1: Participants in the usability experiment.
7.4. EXPERIMENT DESIGN

Figure 7.2: Observational set-up of the experiment. Top: Participant is using the model 2 software program 'Thermanizer’. Bottom: Participant is calculating model 3.

apply the models in case a application problem occurred.

The assignment encompasses the application of models 0 - 3 in a design assignment. The assignment was the same as that described in the pilot experiment. Participants were asked to design the encasing of an electronic product, in this case, a small AC-DC adapter, of which the electronic contents were given (figure 7.1). The designers were given constraints for the design: a maximum hotspot surface temperature of 70°C and maximum encasing dimensions of 60mm × 60mm × 60mm. The power dissipation was given as 4W, which should indicate that the product must be actively cooled.

The goal is to simulate the use of the models as closely as possible and keep assignments as identical as possible for all participants, while randomizing the assignments to control carry-over effects. Video recordings were used to record the experiment. The environment for all cases was a quiet room or a measurement laboratory, specifically designed for observational research (figure 7.2). The recordings have been transcribed for further analysis.

In order to evaluate the applicability, efficiency and quality of the models, several dependent measures have been proposed in tandem with the three dependent variables. Applicability is assessed based on observations. A list of applicability problems has been composed and indicates all problems that were encountered during the study. Re-
results have been used to monitor the proportion of information gained in the experiment by means of a concurrent monitoring method described by Kanis and Arisz [37, 36]. The method is based on applying the well-known statistical binomial model to the rising proportion of shared observations in successive user trials. The authors derive the following algorithm for estimating the total number of problems:

\[
F_\infty = \frac{F_1 \cdot F_{n-1}}{(F_1 + F_{n-1} - F_n)}
\]  

(7.4.1)

\(F_n\) is the amount of problems found after \(n\) participants. \(F_\infty\) is the amount of problems found after an unlimited number of participants completed the experiment. \(F_1\) is the average \(n\) of participants and \(F_{n-1}\) is the average of \(n\) combinations of findings over \(n - 1\) participants. The ratio \(\frac{F_\infty}{F_n} \cdot 100\%\) then indicates the percentage of applicability problems found. The results from applying this method are given in figure 7.3. Since \(F_\infty\) cannot be predicted based solely on the first measurement, the figure consistently begins with Participant 2.

Efficiency is assessed by measuring the duration of certain steps in the experiment. Learning, calculation and interpretation times are therefore measured. The quality of the end result is defined by input, output and design variables. Input variables include all possible variables that the participant can gather to execute a proper approximation of the design. This does not mean that it is necessary to gather all variables. In some cases, fewer variables may be sufficient. The output variables indicate results from using the models. Finally, design variables assess whether the quality of the end result is good or bad. The assignment is given in such a way that the only good design option is to actively cool the device.

The learning effect has been minimized by randomizing the application of models 1-3. Table 7.2 shows the order in which the models are applied during experimentation. Except for the last experiment, Model 0 is applied first because it’s application discusses basic heat transfer theory and is necessary to initiate an understanding for models 1-3.

7.5 Results

Dependent measurements for applicability and quality are given in table 7.3 - 7.6 at the end of this chapter. Applicability problems are indicated in the tables between brackets. An example includes (AP04), which is indicative of the fourth applicability problem encountered during the experiment. The • indicates that an applicability problem occurred during the assignment. A ◦ that a variable is correctly defined or interpreted and a ◆ indicates that a variable is correctly defined or interpreted with the help of the facilitator. The ✗ symbol shows when a variable is wrongly defined or interpreted. Finally, to indicate quality, a + or −, respectively, indicates when a design result is of good or bad quality. The dependent measurements for efficiency are given in table 7.2.

Figure 7.3 shows the results of applying the concurrent monitoring method to models 0-3. Since not all models have been applied by all participants, the number of participants varies. In table 7.2, 7.3, 7.5, 7.6 and 7.7, this is indicated by grey cells.
The usage of model 0 shows that 90% of all applicability problems are discovered, with an estimation of 29 total applicability problems. Model 1 estimates 15 applicability problems, with 87% discovered. Model 2 indicates 29 applicability problems, with 91% discovered. Model 3 indicates 12 applicability problems, with 89% discovered. This suggests that for all models, the experiment results in the identification of most applicability problems.

Table 7.2 gives an overview of learning, calculation and interpretation times. An overview is given of the summation of calculation and interpretation times in relation to the total time taken to apply one of the models. A comparison of these values indicates learning-efficiency, which is the efficiency between learning the models and applying them in a design situation. Learning-efficiency is important because in practice, designers generally must acquire a method before it can be applied. The more efficiently this can be done, the better.

The proportion of calculation and interpretation time (calc+int) to total time (tot.time) is an indication of the learning-efficiency of a model. A model is regarded as more efficient when learning time is relatively small, compared to calculation and interpretation time. Because learning time is a part of the total required time, a high ratio \( \frac{\text{calc+int}}{\text{tot.time}} \) indicates a relatively short learning time and thus a higher learning-efficiency.

With regards to efficiency, model 1 requires the lowest total time, which suggests that this is the most efficient of all of the four models applied. In addition, the ratio \( \frac{\text{calc+int}}{\text{tot.time}} \) is 0.40, the lowest rate. This indicates that learning time is relatively high, compared to the
**CHAPTER 7. EVALUATION THROUGH EXPERIMENTS**

<table>
<thead>
<tr>
<th>Variables</th>
<th>P01</th>
<th>P02</th>
<th>P03</th>
<th>P04</th>
<th>P05</th>
<th>P06</th>
<th>P07</th>
<th>av.</th>
<th>st.dv.</th>
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<th>tot.time</th>
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</tr>
<tr>
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<td>889</td>
<td>322</td>
<td>960</td>
<td>406</td>
<td>691</td>
<td>232</td>
<td>0,50</td>
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</tr>
<tr>
<td>M0 Tot. time</td>
<td>3008</td>
<td>1930</td>
<td>1165</td>
<td>768</td>
<td>960</td>
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<td>1385</td>
<td>934</td>
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<td></td>
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<td>M1 Calc + int</td>
<td>192</td>
<td>209</td>
<td>279</td>
<td>151</td>
<td>511</td>
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Table 7.2: Experiment data.

Calculation + interpretation time. In addition, model 1 can be applied relatively quickly once it is understood. The same ratio \( \frac{\text{calc} + \text{int}}{\text{tot.time}} \) equals 0.82 for model 2. This suggests that the model is relatively easy to learn, when compared to the time that it takes to apply. Therefore, it has the best learning efficiency. Model 3 requires the highest total time, which could indicate overall low efficiency. In addition, the calculation + interpretation time is highest for this method. This indicates that model 3 is probably most difficult to apply. This assumption is also motivated by the fact that with this model, the design score is bad in all cases (table 7.6) and that it is perceived as difficult to understand and difficult to use (Q1 and Q3 table 7.7).

In the cases of models 0 and 1, the problem seems to be difficulty in defining the input variables. Three out of six (table 7.3) and four out of seven (table 7.4) participants calculated the area incorrectly! For models 2 and 3, the problem seems to be interpreting the results. For method 0, methods 2 and 3 require a fairly advanced understanding of the principle of thermal RC-nets.

Opinions of the participants have been evaluated by means of a debriefing questionnaire (appendix D), which is composed of sections with both closed (table 7.7) and open questions.

Generally, models 1 and 2 are seen as easier to use when compared to models 0 (the standard way) and 3. One exception is Participant 7, who believes differently (Q01). Models 1 and 2 score better on satisfaction for obtained results (Q02). Model 1 is seen as the easiest model to use, while model 3 is the most difficult to use (Q03). Most participants are positive about using models 2 and 3 during the design process. Models 1, 2 and 3 are perceived easier to remember when facing a future design situation, compared to the standard way of modeling (Q05). The most significant dangers afflicting these models are that they are used incorrectly and are inaccurate (Q07). All respondents replied that they had not used other methods that were comparable to the ones tested, which could indicate that the models would be an improvement, compared to current practice (Q08). All models score relatively well on application time, compared to model 0. Participants perceive model 1 as very quick to apply. Models 1 and 3 are seen as less reliable (Q11). Models 2 and 3 are perceived as giving the most accurate results (Q12).

According to participants, the advantages of using models 1-3 include ease of use, efficient and fewer mistakes. Model 1 is seen as giving a good first approximation, while
models 2 and 3 give more insight in visualizing concept changes. For example, Participant 7 wrote, "Model 1 can be used in an early stage; model 2 and model 3 are easy to [use to] evaluate adjustments." In general, these models are seen as a means for improving communication between engineers (hardware, software, design) working together. Participants seem positive viewing the models as a means for preventing errors during latter stages. Accuracy and validation are seen as major problems incurred when using these models. Participant 6 noted, "With model 1 and model 2, there is no insight behind the model. Designers then do not know what to look for." Possible improvements include additional and better visualizations and integration of the models into a software package.

7.6 Interpretation and conclusion

Results indicate that for all experiments, about 87% - 91% of all applicability problems have been identified. These results can be used in future research to optimize the applicability of the models. Model 1 can be regarded as the most efficient in the sense that it can be quickly applied and calculation + interpretation time is very low, averaging 5:44 minutes. Method 2 is the second fastest method. Required learning time is the lowest of all methods. Calculation + interpretation time, however, is high, at 15:10 minutes on average, suggesting that results from the method provide the designer with a great deal of information. For model 2, the main problems with applicability appear to be understanding input variables. Once the variables and functioning of the program are known, application happens very quickly. However, interpreting the four graphs from model 2 is difficult if the basic ideas of transient heat transfer are not understood. Method 3 requires the highest amount of time for application and calculation + interpretation. However, learning time is the second lowest. It is suggested that the learning speed of M1 and M3 can be improved by integrating models into a software package, comparable to model 2. Adding more clarity to the input variables, for example, giving explanations through drawings, has also been suggested.

The models presented in this thesis are still in the preliminary stages of development. Using novice designers, who have little background in heat transfer, is seen as a proper approach for defining issues requiring further development. However, by continuously improving the models, it also becomes more advisable to execute similar studies that involve participants who are experienced in the field of heat transfer and thermal design of electronic products.
**Applicability problems**

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<th>P04</th>
<th>P05</th>
<th>P06</th>
<th>P07</th>
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<tbody>
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**Input variables**

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<td>x●</td>
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**Design variables**

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Table 7.3: Evaluation of model 0.
7.6. **INTERPRETATION AND CONCLUSION**

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Table 7.4: Evaluation of model 1.
### Applicability problems

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Table 7.5: Evaluation of model 2.
### Applicability problems

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<td>$T_m/\Delta T$</td>
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### Design variables

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Table 7.6: Evaluation of model 3.
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<td>Q04 Would you use the models in your design process when it becomes fully operational and matched to specific design cases?</td>
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<td>Yes</td>
<td>Yes</td>
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<td>Q06 Does this model easily recover errors or wrong design decisions in a conceptual design?</td>
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<td>M1</td>
<td>M0</td>
<td>M2</td>
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Table 7.7: De-briefing questionnaire for perceived usability.
Chapter 8

Evaluation of the applicability, efficiency and quality of the three models through interviews

Five of the participants that took part in interviews described in chapter 3 were interviewed again to discuss the three models and the results of the experiments described in the previous chapter. The aim of these interviews is to verify opinions of design experts on the applicability, efficiency and quality of the three models.
8.1 Introduction

This chapter focuses on the verification of applying models 1, 2 and 3 to the design process by means of interviews with designers from the field and answers the following question: What do design experts think about these models and methods? The results give insight into the propositions stated at the beginning of this thesis. Five practicing designers were interviewed on the models and the results of the verification experiment.

8.2 Goal and approach of the interviews

The goal of the semi-structured interviews in this project is to obtain an evaluation of the models based on how people from practice view them. Present interviews give insight into the value of the three developed models in practice. As has been previously proposed, the three models should optimize the design process. The following three criteria are the main focus regarding optimization of the design process:

Criterion 1  Applicability of the models.
Criterion 2  Efficiency of the design process.
Criterion 3  Quality of the products.

With regards to the research project itself, three other criteria will be discussed and include the following:

Criterion 4  Have correct propositions been used?
Criterion 5  The generality of the models.
Criterion 6  Suggested improvements.

The approach involves preparing a semi-structured interview to evaluate the three models that have been developed and the results of the experiment described in the previous chapter. A requirement of the semi-structured interviews is to prepare the participants and allow them to become familiar with ideas behind the models. This was realized by sending the participants a document in which the models and the results of the experiment were explained and by including a list containing the questions that would be discussed during the interview. Five participants most closely related to the development of commercial and mass-production consumer goods were chosen from the people that participated in preceding interviews.

Prior to the evaluation interviews, an overview of the research and an introductory letter was sent to the participants. Table 8.1 shows the main questions used to structure the interviews; these were also described in the introductory letter. The overview of the study contained an explanation of the goal of the research project, the three models and methods developed and the outcome of the usability experiment. In the letter, the main
8.2. GOAL AND APPROACH OF THE INTERVIEWS

<table>
<thead>
<tr>
<th>General questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) For which type of products are the models most appropriately applied? (criterion 1: applicability)</td>
</tr>
<tr>
<td>2) At what stage in conceptual design can the models be used? (criterion 1: applicability)</td>
</tr>
<tr>
<td>3) For which type of designers are the models most appropriate? (criterion 1: applicability)</td>
</tr>
<tr>
<td>4) Does application of the models speed up the design process? (criterion 2: efficiency)</td>
</tr>
<tr>
<td>5) Does application of the models prevent design errors and result in less design iterations? (criteria 2 and 3: efficiency and quality)</td>
</tr>
<tr>
<td>6) Are the models based on correct assumptions/requirements as have been described in preliminary research? (criterion 4: propositions and criterion 5: generality)</td>
</tr>
<tr>
<td>7) How can the models be improved? (criterion 6: improvements)</td>
</tr>
</tbody>
</table>

Table 8.1: General evaluation questions.

questions that would be asked during the interviews were also outlined. Some participants introduced a colleague, who also participated in the interviews. These participants are indicated using extensions A and B.

During the interviews, participants were first acquainted with the goal of the interview and informed of its outline and the approximate time of one hour it would take to complete. Even though participants had already received a summary of the research results, a small presentation of the three models and methods was given in order to bring them up-to-date on any further developments. The interview then followed with a discussion of the topics based on the questions. The interview finished with a debriefing, in which a summary of the conversation was completed. The participants were also asked if they had any questions and whether or not they were interested in the outcome of the interview. All interviews have been transcribed so that the most pertinent quotes could be shared. In the results section, comments made by participants are classified into six categories, representing the six criteria. The views of participants on these criteria will be discussed per category. Participants can be described as follows:

**Participant 1** is a design engineer who works in a company that designs professional cameras. The design process resembles a concurrent engineering process in which the mechanical, hardware and software designs are performed in tandem.

**Participant 2** is a thermal design expert who is involved in development processes for a large manufacturer of consumer goods.

**Participants 3A and 3B** work for a company that develops electronic products for other manufacturers. This process can also be characterized as a concurrent engineering process.

**Participant 4** has his own design agency. The designer works together with electronic developers (other companies) and is mainly involved in the mechanical encasing of electronic products.

**Participants 5A and 5B** are mainly involved in the detailed redesign of a module used in many consumer electronics.
CHAPTER 8. EVALUATION THROUGH INTERVIEWS

8.3 Results

This section will present the results of the interviews. Results are derived from transcripts of the interviews, which have been labeled and categorized [2]. Results are first categorized according to the six criteria: applicability, efficiency, quality, propositions, improvements and generality. Then, results are described and interpreted separately for each participant. Because of the semi-structured nature of the interviews, not all issues have been discussed with all participants. The following paragraphs aim at presenting the views that participants have on the criteria.

The applicability section discusses what participants think about the applicability of the three models with regards to their individual types of development projects. The efficiency section presents comments of participants explaining how these models may speed up the design process. The quality section discusses whether or not the models improve the quality of the product. The proposition section discusses whether or not the models are based on correct propositions. The improvements section details suggestions made to improve the models. The generality section discusses the extent to which participants expect the models to predict satisfactory results when applied in practice.

8.3.1 Criterion 1: Applicability

In this section, applicability will be discussed. Here, the focus is on to what extent the models are practically applicable to participants.

According to Participant 1, model 1 is applicable when choosing between active and passive cooling. However, he does not have confidence in the exact outcome of the model. Model 2 gives insight into the factors that determine the heat path and evaluates the effects of specific design changes. However, it is not seen as reliable enough to sufficiently calculate accurate temperatures. Model 3 would require a background in heat transfer knowledge for its application. One participant explained that he or she had used a similar approach to model 3 in a previous design project. In this case, only one thermal resistance was determined, but was based on measurements. The participant explained that he or she preferred using a software program.

Participant 2 describes model 1 as a good ‘risk assessment’ tool that may be more applicable by integrating air flow into the basic formula as in the following:

\[ q = hA\Delta T_{\text{encasing-ambient}} + \dot{V}c_p\rho \Delta T_{\text{air flowin-air flowout}} \]

Although he found the model interesting, the participant mentions that it is probably more suited to thermal design experts. The transient approach is also a good approach, but merely for an expert. He suggested that if designers are going to use model 2, it may be necessary to use some sort of ‘fuzzy-logic’ interface that focuses on design choices, such as radiation on or radiation off. An additional concern is whether or not models 2 and 3 give an accurate prediction for a printed circuit board with more than one component, which is usually the case in practice. Finally, model 3 is seen as applicable in a thermal management algorithm that would protect a device if it approaches the danger zone—a
transient model is needed to complete predictions, but this is seen more of an expert action than something for the industrial designer. In general, the participant opinions on models 2 and 3 are similar to the following: “I think that model 2 and model 3 simply are too complicated for most designers. I also doubt the applicability of the models in practice”.

Participants 3A and 3B describe model 1 as suitable enough to convince managers of design choices such as whether or not to include a fan in the design. Model 2 is found interesting, but should focus more on evaluating practical solutions, specifically, the heat path from a component to the ambient environment. An example given is the difference between conductive paste and gap fillers. Model 2 is seen as a good back-up for defending design decisions to managers because quantitative data is usually more convincing than design choices based on experience. In general, the applicability of the models is regarded as sufficient because they result in a method that assists in visualizing problems detected through figures and graphs.

Participant 4 finds model 1 interesting because it shows the order of magnitude in which problems can be expected. Such a model may work very well in practice. It is easily understood and designers do not need to solely rely on “assumptions” until a prototype is developed. Electronic designers could also use this model. This participant was not familiar with RC-networks and did not comment on models 2 and 3.

Participants 5A and 5B would not use model 1 because they usually work on very precise levels. However, these participants do think that model 1 is useful to people that develop different types of products (e.g., designers from design agencies). Model 2 has a great deal of potential, however, before one can take advantage of its effectiveness, “gathering the required design parameters” is required, which can be very difficult. These parameters must be measured during application. But, if a software program could complete this type of prediction, these participants would be more willing to use the model. It is not very applicable to develop a flexible software program for model 2. Instead, it is more practical to change the values and see what the effect is on temperature. Both participants 5A and 5B seem uninterested in a hand formula, such as model 3.

8.3.2 Criterion 2: Efficiency

In this section, the effects that model application have on the efficiency of the design process are discussed.

Participant 1 states that efficiency mainly entails having something with which to make estimates. This participant also explains that in order to make comprehensive calculations, a great deal of time is invested into remaining up-to-date. The participant further explains, “The common designer cannot rapidly calculate something such as the formulas presented in models 1-3. Usually, your knowledge is insufficient and costs much time to sort it all out. That is why you can reach enormous efficiency if you can do something, such as [using] these models.”

Participants 3A and 3B are very specific in the level of efficiency that can be reached by applying the presented models. For model 1, pictures can help speed up the design process by giving extra motivation and preventing time from being wasted convincing
someone, usually a manager, of a design’s worth, who views the design or decision as impractical: “It helps if you can show a picture [model 1 and model 2]. With this, you can speed up the design process because it sometimes costs about four weeks extra work to support your decision and extra time because someone otherwise will not believe you. Four weeks might even be an underestimation”. Model 2 can save time defining the maximum cooling limit. It is useful for saving time by convincing a manager to disallow the start of a trajectory for a solution believed to be of poor quality. Model 3 is also seen as a method that could improve efficiency. Participant 3B stated that you can save a great deal of time if a model is derived from measurements and can be used to predict the effect of different configurations: “[Executing] all of those measurements can take up to a few weeks”.

8.3.3 Criterion 3: Quality

Here, results referring to the improved quality of designs are presented. Therefore, the focus will be on the relationship between the models and the physical design.

Participant 1 explained an example in which he tried to produce a similar graph as model 1. Model 3 can be used, according to the participant, to evaluate design decisions. The participant also explains that transient analysis is not as pertinent to his applications because the devices that he designs almost always reach steady-state. In addition, the participant doubts that a mock-up can be used to give a representative approximation and thinks that model 3 could be used only very late in the design process when a functional model is available. If the costs are compared with hiring a company that does thermal testing and simulation, there would definitely be a budget for a software program simulating thermal design.

Participant 2 suggests that model 1 may provide a good initial estimation for somebody who is unfamiliar with heat transfer. It would allow him or her to discuss active versus passive cooling and decide whether contacting a specialist is necessary. Most engineers will analyze a situation first if they are unfamiliar with the product. This participant also indicates that the model 1 approach could be used for module and component levels, but more flexibility with regards to choosing parameters should be introduced (e.g., being able to adjust the heat transfer coefficient of convection, to determine whether passive or active cooling is needed). The participant recognizes the application of model 2 from compact models. The participant also believes that this method can be applied to system, module or component levels to analyse the heat path through the system and find the most critical areas.

Participants 3A and 3B see the advantage of the models through their ability to create pictures. These pictures can be used to support design decisions and convince management and clientele. For example, model 1 can be used to support the decision to integrate a ‘back-up’ for active cooling in design because the power trend can be visualized. The simple calculations that are usually done by manufacturers can now be done by designers or engineers themselves. Participants also state that there is an element of danger involved when wrong values are filled in. The participants also explain that model 2 and 3 are useful when they can be used to analyze the heat path so that design decisions, or
8.3. RESULTS

rather, solutions with regards to the thermal ‘interfaces’ in the heat path, can be evaluated. Participants could see themselves using this type of model for specific applications, such as conductive paste, gap fillers, cooling fins and so on. Model 3 can be used during the development of a platform: “If you have calculated this product once and used model 3, it could be very conveniently used to evaluate if, for a following design, a problem occurs. This could be very convenient”. With regards to the quality of applying these models, one participant specifically stated that he does not trust software programs and would prefer to use formulas from a handbook because he believes this gives him more control.

Participant 4 recognizes calculation methods from suppliers of cooling equipment. The participant thinks that if model 1 is used, the designer may not attempt to try alternative solutions. He is also of the opinion that designers usually work in a “transitional area”. However, this participant can see the order of appearance for design models in the design process and also states: “Model 1 could be a good step in the direction of a discussion with electronic designers”.

8.3.4 Criterion 4: Propositions

This section will discuss whether models are based on correct propositions. We recall the following propositions:

1. Many designers are unfamiliar with heat transfer theory and thermal design theory. Such designers lack the basic knowledge to make basic design choices and evaluate how important temperature will be in the design.

2. Evaluation of structural concepts on temperature development is not supported by a standard approach.

3. Temperature measurements are crucial to thermal design in practice.

Participant 1 executed similar analyses, also based on measurements, to predict what happens to temperature if power is reduced. He explains that theoretical models are difficult to validate, but semi-empirical models based on measurements can predict outcomes with a high level of reliability and confirms the assumption that FEA and CFD are difficult to interpret without hand calculations. He further implies that it is necessary to use these calculations during preliminary phases when describing a current project: “We are using a similar approach [model 3] relatively late in this project. However, this is not really an example project. The fact that you are doing these types of calculations during this stage is a little bit sad. This is something you would not want, to find out that the encasing is far too hot and you cannot do anything about it, other than changing the specifications”.

Participant 2, the thermal design expert, is confronted with many design projects that are not based on proper front-phase analysis. He finds it a positive goal and believes it necessary for designers to incorporate knowledge of thermal design. The participant explains that many handbooks exist on this subject, but usually focus on heat transfer
calculations in different situations, rather than applications for products, such as a simple box. He explains that models comparable to model 1 are already in use. This participant expects that most companies that manufacture consumer products have somebody who computes thermal spreadsheet calculations. With regards to computational fluid dynamics, he says, “You can calculate many things, but CFD is always slow. So, if you can develop a feeling for it, that would be a good thing.” Model 2 is also practically applied, but is usually only used to model the heat path of on-chip packages. According to the participant, it is also good to include the transient effect. Sometimes, the user profile is such that the product does not reach steady-state: “What you are doing with steady-state is determining the total thermal resistance; this, however, does not show where the restrictions are”.

Participants 3A and 3B have used detailed models in the past, but did not find much use in them. Model 3 is seen as something that is most useful if starting from scratch. Usually, one will create a mock-up because it takes too much time to thoroughly explore the subject of thermal analysis. Model 3, although also seen as more of an expert action, is a helpful tool: “The good thing about this is that you can combine a theoretical model with a real model”.

Participants 5A and 5B describe that for their projects, measurements are a significant means of defining correct heat transfer coefficients. However, they work on a much more detailed level than is intended with models 1-3 and explain that they would not use them unless the R’s and C’s are flexible enough to incorporate into a software program. They do, however, elaborate that model 1 type tools are actually used in other departments of the company as a risk analysis. These participants have completed transient calculations, however, do not actually use these calculations in the thermal management algorithm in their product and do not see it as a necessity.

8.3.5 Criterion 5: Improvements

During the interviews, participants often made suggestions about how to improve the models. These suggestions are described below.

Participant 1 suggests not using many configurations because they will make things unnecessarily complex. The models should also integrate the use of more than one hotspot. It would also be nice to be able to view a different axis in model 1. He is interested in seeing what the effect of changing one variable has on different configurations. The configurations would be more understandable if visualized in a realistic manner because visualizations are a necessary tool for the designer to communicate his ideas.

Participant 2 proposes using model 1 as a risk assessment tool to evaluate if a designer needs to contact a specialist to integrate airflow through the device. Model 2 can be used to develop a semi-empirical model for thermal management algorithms.

Participants 3A and 3B suggest integrating an option that warns about problem situations and shows the maximum temperature of all components in the device. In addition, they suggest having an option that would allow for the visualization of models in a more ‘realistic’ way, for instance, blocks that can be attached to each other using a ‘wizard’
8.4. COMPARISON AND CONCLUSION

that helps estimate heat transfer coefficients. Model 2 would be most helpful if used to quickly evaluate the heat path in structural variants during conceptual design. It should also give examples and a list of key points for non-experts. Additionally, the models should be developed into a web-based tool.

Participant 4 suggests improving the readability of model 1. He also states that designers are usually more interested in solutions. Participants 5A and 5B suggest integrating the maximum allowed temperature of components in the models and giving examples of this. RC-networks should be adjustable and include a wizard to compute heat transfer coefficients.

8.3.6 Criterion 6: Generality

This section discusses how participants regard the generality of the proposed models. Here, generality is defined as the applicability of these models to other electronic product designs than the AC-DC adaptor described in this thesis.

Participant 2 claims that model 1 can be used, but restrictions must be very clearly defined: “I think you can use it if you clearly explain the restrictions. This is important for a designer that does not have any knowledge of heat transfer”. Model 1 is also a good tool for estimating whether a calculation is correct or not. However, one must realize that there are sometimes specific specifications for modules. Modeling components for a print would require a more detailed resistor network than available in model 2. He explains, “You can test this on a simple system and I find this a good action because you can see if you can go further than just the heat dissipation in a box with arbitrary heat transfer coefficients on the outside. However, in practice, you must deal with rather complex geometries. Especially for free convection, this is difficult to predict.”

According to participants 3A and 3B, model 1 cannot be applied to predict local hotspots. The accuracy of the predictions (model 1-3) are very much dependent on how good the estimations for parameters are. Model 1 cannot help make decisions on detailed levels. Model 3 can only be used to optimize the detail level. It does not prevent one from making wrong decisions on a structured conceptual level: “You need a detailed level design to use model 3. So, in this phase you have already made decisions that you can optimize on a detailed level, but it does not support optimizing the structural concept” (and thus does not prevent one from making incorrect design decisions on a conceptual level).

8.4 Comparison and conclusion

In this section, the three models will be evaluated. Table 8.2, table 8.3 and table 8.4 show a qualitative evaluation of the results indicated by a + or a - . This is done for all criteria, except improvements. Improvements are indicated with a ◦.
## Model 1

A comparison of table 8.2, table 8.3 and table 8.4 indicates that model 1 was, for the most part, positively evaluated. Although the model has a rather specific application, mainly in the form of risk analysis, several suggestions are made to make it applicable in a variety of situations and for more specific application areas. All in all, it is viewed as a valuable tool for its intended purpose, which is evaluating active versus passive cooling. Even designers that routinely use advanced thermal design tools, such as CFD, confirm that model 1 is a tool that should be used during early design stages. Model 1 can therefore be meaningfully applied by engineers familiar with high-end thermal analysis tools, but also by designers who are only incidentally involved in thermal issues. In fact, model 1 is the only model that is consistently evaluated as a helpful tool for conceptual design. Results indicate that this type of tool is one of the few models that can be applied by designers unfamiliar with heat transfer. Model 1 is also the only model regarded as generally applicable in design as a risk assessment tool.
### Table 8.3: Evaluation of criteria with regards to model 2.

<table>
<thead>
<tr>
<th>Crit.</th>
<th>Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Appl.</strong></td>
<td>Most participants prefer the use of a software program.</td>
</tr>
<tr>
<td>-</td>
<td>Participant 3B is a bit skeptical towards software programs.</td>
</tr>
<tr>
<td>-</td>
<td>Some participants are unfamiliar with the use of RC-networks for temperature calculation.</td>
</tr>
<tr>
<td>-</td>
<td>Participants 5A and 5B find the approach too rigid for their purposes.</td>
</tr>
<tr>
<td>-</td>
<td>Participant 2 thinks that models 2 and 3 are too complicated for designers.</td>
</tr>
<tr>
<td><strong>Eff.</strong></td>
<td>Defining the maximum cooling limit may prevent managers from inhibiting the start of a trajectory.</td>
</tr>
<tr>
<td><strong>Qual.</strong></td>
<td>Helpful for defending decisions to managers and clients.</td>
</tr>
<tr>
<td>+</td>
<td>An interesting concept for evaluating a specific heat path.</td>
</tr>
<tr>
<td>-</td>
<td>The biggest problem is finding correct local heat transfer coefficients.</td>
</tr>
<tr>
<td>-</td>
<td>Not appropriate for calculating more than one hotspot.</td>
</tr>
<tr>
<td><strong>Prop.</strong></td>
<td>The approach is recognized from transient thermal testing of systems-on-packages.</td>
</tr>
<tr>
<td>+</td>
<td>Participants 3A and 3B like the idea of a formula used to evaluate heat paths.</td>
</tr>
<tr>
<td>+</td>
<td>The transient approach is an improvement, compared to the usual steady-state approach.</td>
</tr>
<tr>
<td>-</td>
<td>The approach presented here is not needed (stated by participants 5A and 5B).</td>
</tr>
<tr>
<td><strong>Impr.</strong></td>
<td>A fuzzy-logic approach is suggested as more appropriate for designers.</td>
</tr>
<tr>
<td>○</td>
<td>More flexibility with regards to changing the RC-network to reflect specific applications is needed.</td>
</tr>
<tr>
<td>○</td>
<td>Present the models with a more ‘realistic’ picture.</td>
</tr>
<tr>
<td>○</td>
<td>Focus on heat paths in specific situations.</td>
</tr>
<tr>
<td>○</td>
<td>Make variations to include more hotspots.</td>
</tr>
<tr>
<td><strong>Gen.</strong></td>
<td>Participant 2 questions if the correct RC-network has been used.</td>
</tr>
<tr>
<td>-</td>
<td>It is very difficult to fill in the correct parameters.</td>
</tr>
</tbody>
</table>

**Model 2**

Most participants prefer the use of a software program. Model 2 is therefore seen as an applicable approach, although some changes are proposed to improve practical applicability. Model 2 is seen as a means of evaluating a specific heat path. Application of the model could improve the efficiency of the design process by preventing wrong conceptual decisions. However, the model is not seen as generally applicable, since most products have more than one hotspot. The reliability of the results, especially in the case of natural convection, is discounted by some participants because of the complexity of the phenomenon. It has been suggested that model 2 is too complicated for the common designer. The transient approach is generally seen as a valid method and an addition to commonly used steady-state models. Model 2 is not seen as generally applicable by most participants because of two issues. First, the model only predicts the temperature of one hotspot, while most electronic products have more than one. Second, the prediction of local heat transfer coefficients is very difficult and crucial regarding the reliability of the prediction.
CHAPTER 8. EVALUATION THROUGH INTERVIEWS

<table>
<thead>
<tr>
<th>Crit.</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appl.</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>- A theoretical approach is not practical for most participants.</td>
</tr>
<tr>
<td></td>
<td>- The concept behind model 3 is difficult to grasp by most participants.</td>
</tr>
<tr>
<td></td>
<td>- RC-networks are difficult to comprehend for most participants.</td>
</tr>
<tr>
<td></td>
<td>- More flexibility in choosing the RC network is required.</td>
</tr>
<tr>
<td>Eff.</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>The main advantage is that such a model can be used to convince project management.</td>
</tr>
<tr>
<td>Qual.</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Semi-empirical models reduce measurement time.</td>
</tr>
<tr>
<td></td>
<td>+ Can be helpful when developing a new platform to predict when problems will occur.</td>
</tr>
<tr>
<td>Prop.</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Formulas such as model 3 are not needed.</td>
</tr>
<tr>
<td></td>
<td>- Some participants do not see the advantage of a transient analysis.</td>
</tr>
<tr>
<td></td>
<td>+ Most participants confirm using empirical or semi-empirical models in design.</td>
</tr>
<tr>
<td></td>
<td>+ The transient effect should be taken into consideration.</td>
</tr>
<tr>
<td></td>
<td>- Mock-ups are usually used when designing detail.</td>
</tr>
<tr>
<td></td>
<td>- Model 3 is more applicable for the detail phase.</td>
</tr>
<tr>
<td>Impr.</td>
<td>◦ The concept of RC-networks is more related to real situations.</td>
</tr>
<tr>
<td></td>
<td>◦ Make variations to include more hotspots.</td>
</tr>
<tr>
<td></td>
<td>◦ Turn it into a software program with a wizard to estimate boundary conditions.</td>
</tr>
<tr>
<td></td>
<td>◦ Do not make too many complex configurations.</td>
</tr>
<tr>
<td>Gen.</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Participant 2 doubts if the model can be generalized for real situations.</td>
</tr>
<tr>
<td></td>
<td>- The nonlinearity of heat transfer coefficients is seen as a problem regarding generality.</td>
</tr>
</tbody>
</table>

Table 8.4: Evaluation of criteria with regards to model 3.

Model 3

Applying model three during conceptual design is not advised. Most participants prefer the use of a software program and do not see the value of a theoretical approach. Although transient analysis is viewed as a good proposition, the concept behind model 3 is difficult to grasp by designers with little background in heat transfer. Model 3 is, however, seen as an applicable tool to calculate the thermal management algorithm in order to protect a device during use, although this is more the responsibility of an expert, rather than a designer. The use of model 3 during the conceptual design phase is questionable and is more appropriate for use during the detail phase of design, where empirical or semi-empirical models are more frequently used. This model can be a good tool for semi-empirical modeling, but does not give a solution for optimizing structural design configurations during the conceptual design phase.
Conclusions and recommendations

This chapter discusses the main research question and gives recommendations for further research.

What’s next?
Has the objective been reached and where do we go from here?
CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

Thermal design is a hot issue in product development. This thesis has asked the following question: *How can thermal design of electronic products be optimized in the conceptual phase of product development?* The research work presented in this thesis uses a structural approach to answer this question. Preliminary research resulted in a definition of three main problems. Based on this preliminary research, three tools and application methods were developed as solutions. These tools and methods have been evaluated by means of usability experiments and interviews with design experts.

The first defined problem is that many designers are unfamiliar with heat transfer and thermal design theories. Such designers lack the knowledge to make basic design choices and evaluate how important temperature will be to the design. To help alleviate this problem, model 1, a rule-of-thumb solution, has been developed. Model 1 is easy to use and generally applicable to most electronic products under normal use conditions. The model is not valid for specific applications, such as high altitude and critical outdoor applications.

The second defined problem is that evaluating structural concepts for temperature development is not supported by a standard approach. For this, model 2 has been developed. Model 2 is a software program that computes the heat path by means of a linear RC-network. The model is good for approximating the heat path, but requires some background in thermal design for proper application. Both model 1 and model 2 can improve the efficiency of the design process. According to some participants, a reduction of several weeks work is possible.

Finally, it has been concluded that temperature measurements determined using mock-ups and functional models are crucial in practical thermal design to find reliable heat transfer coefficients. For this, model 3 has been developed. The concept of model 3 is to provide an RC-network that can be calibrated through measurements calculated using a functional model for a thermal mock-up. Model 3 is a specialist action. However, the concept is useful and, in some cases, currently applied by thermal design specialists. The application of model 3 is therefore appropriate during the detail design phase and for application in thermal management algorithms to predict and control hotspot temperatures during product use.

9.2 Answer to the main question

Thermal design in the conceptual phase can be improved by several means. First, designers can use the graph and rule-of-thumb approach that is embedded in model 1. By using this, the most important structural concept decision regarding thermal design can be made: Should active or passive cooling be applied? In addition, the designer obtains some idea about the importance of the role that thermal design will play during the development process. If the design is critical, the designer can choose to contact a thermal design specialist to help define an optimal structural concept early in the project. This saves time and will most likely result in a design that is less vulnerable to after-defect
9.3. SCIENTIFIC RELEVANCE OF THE APPROACH

solutions.

A second step should include having the designer gain some background in heat transfer so that the concepts behind models 2 and 3 can be understood and applied. For this, it is necessary to expand these concepts into various ranges of solutions to evaluate the heat path in several structural concepts. This approach is comparable to the approach of mechanical design, which has been successfully applied for many years. However, before reaching this stage, a tremendous amount of experience data and modeling must be studied.

9.3 Scientific relevance of the approach

This thesis covers research in the field of design engineering. One of the focuses of this field is transferring scientific knowledge to design. This can be done by defining the main problems present in analysing research and practice. Here, the goal is to improve product development from a competitive and sustainable point of view. The main criteria for transporting knowledge to practice is usability, defined as the efficiency of the design process, the quality of the resulting products and the practical applicability of the models. The scientific relevance of this thesis can be explained using this view on design engineering research. In order to transport knowledge from theory to practice, a combination of scientific literature and interviews engaging design experts has been used. This study shows that such an approach, in which the systematical use of available theory and knowledge of experts in the field, results in suggestions that can reduce the time needed to complete the product development cycle (chapter 8). The reliability and quality of these products can be guaranteed (chapter 7). Finally, costs and reliability can be controlled by properly using the presented methods, making them practically relevant.

In the field of design theory verification, this thesis shows the application of usability experiments and semi-structured interviews. To the best knowledge of the author, the usability of thermal design tools has not been studied until now. The usability experiment in this thesis is revolutionary for this type of research in the field of thermal design and heat transfer. In summary, this research has shown that integrating research methods and combining them with the field of design results in scientific progression in the field of design. Usability experiments and semi-structured interviews can be a means of moving technological knowledge from research to practice.

9.4 The generality of the models and methods

In this thesis, three models have been proposed to help solve specific issues in the thermal design of electronic products. Model 1 is regarded as generally valid for electronic products used under normal conditions. Exceptions include products that must work in extremely ambient conditions, such as those operating at high altitudes, outdoors or with specific ergonomic requirements regarding encasing temperatures. Important guidelines for applying this model include the realization that it does not prevent occurrences of or
solutions for local hotspots. Model 2 can compute hotspot temperature with an accuracy of 20%, which is accurate enough to evaluate structural concepts during early design stages. However, this model only discusses the heat path for one single hotspot and, therefore, cannot be generally applied to all products. The need for development and verification of similar models with the ability to locate several hotspots has been advised by several participants during interviews and is suggested for consideration in future research. Model 3 is seen as a valid method for approximating temperatures in steady-state situations, once boundary conditions have been calibrated using measurements obtained from a thermal mock-up for a functional model. Global thermal capacitance can be derived from measurements using the transient behavior of a specific heat path by means of the unconstrained minimization method. However, the model does not support transient behavior for devices in which there are significant differences in time constants. Completing a curve-fitting analysis using detailed RC-networks is suggested.

9.5 Recommendations for future research

Developing and applying the models and methods has resulted in insight for several areas of design research. Research methods used in this study encompass desktop literature research, semi-structured interviews, theoretical and numerical modeling and measurement and qualitative user experiments. A comparison of theory and practice has been identified as a method for obtaining direction in design research. Because design is an area of integration, part of the research in this field should focus on integrating and transporting theories to practical application.

The presented research shows how difficult it is to strictly verify models and methods using experimentation. In chapter 7, the problem with the level of minimum proficiency needed by novice participants to obtain a proper application of the models was identified. This aspect has been very difficult to realize and deserves further discussion. Future design research should focus on methods of ‘verification’ for models and methods employed by the industrial designer. This is necessary because, in many cases, designers are not experts in all ranges of design subjects. In order to increase applicability, efficiency and quality within the design process, pre-education should be one of the main focuses in design research. In this research project, time constraints available for the usability experiment resulted in using novice designers as participants. It is suggested that conducting a similar usability experiment with experienced designers will result in other observations than those presented in this thesis.

With regards to the models presented, model 1 has been deemed the most successful design tool for practice. It fits the fact that most designers are unfamiliar with heat transfer and thermal design. This model also gives the designer a clear view and direction in design and forces him or her to decide whether or not active cooling is necessary. Recent discussions with thermal designers from a major electronic products manufacturer resulted in the conclusion that comparable models have already been successfully applied in practice as a form of risk assessment.

Model 1 still needs some research in order to make improvements in the application
9.5. RECOMMENDATIONS FOR FUTURE RESEARCH

Figure 9.1: Example of an improved visualization of an RC-network.

area (e.g., high altitudes) and extend the model using forced convection. The basis is clearly present and available for improvements.

Model 2 can also be further developed. The amount of input for parameters should be restricted to thermal resistance and capacitance. In this way, the designer can freely evaluate the heat path. This model also forces the designer to think about the concept of thermal resistance and capacitance. This physical insight gives a better basis for discussing improvements in design. The interviewed participants indicated finding simple software programs preferable to other methods, graphical or theoretical. Visualizations are also seen as an important aspect for convincing others of design decisions.

Further development of the concepts for model 2 could focus on defining standard heat paths or cooling situations often encountered in electronic products. In addition, the designer should have some freedom to adjust models to fit specific applications. For instance, a small wizard could be integrated to help the designer define heat transfer coefficients for radiation, conduction and convection for most practical problems. With regards to applicability, integrating different graphs into one graph showing the total transient behavior from the hotspot to the ambient environment is recommended.

With regards to the generality of the models, additional research must still be completed. The definition of reliable heat transfer coefficients is an issue that requires attention, especially when applications, such as model 2, are used by designers who are not experts on a particular subject. Integrating several hotspots into the models is also an issue that will require additional discussion.

Model 3 is appropriate for the detail and implementation phases in design. From the interviews, it has been determined that such approaches can have benefits in thermal management and in modeling thermal behavior in the development of product platforms. However, the required level of detail and proficiency on the part of the user suggests that the method would be better applied to the final stages of design. It is also advised that RC-networks be represented in the form of a practical application. An example of this is
CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

Given in figure 9.1.

Extending the research to develop variations of model 3 is important. Research on empirical “experience” data can also give the designer something to embrace during the design process that would improve predictions (temperature approximations) and explorations of structural concepts during the early stages of design. This has already been extensively applied in the area of mechanical design and published in handbooks, which have shown their efficiency in practice. This would be a logical step to repeat during the thermal design of electronic products. However, this would require an extensive amount of empirical research on practical and applicable models and field values.

Several other things can be done to improve the thermal design of electronic equipment. The approaches and materials currently used are, in the author’s opinion, still rather conventional. The focus on new materials and integration techniques should be further studied. A good example of this is the study described by de Jong et al. [14]. Research in industrial design could focus on applying thermally conductive polymers and embedded electronics to improve the spreading of heat throughout a product on module and system level.

This thesis has shown, for the first time, the application of an approach that combines scientific literature and interviews with practicing designers in the field of thermal design research. This approach, in which the systematic use of available theory and knowledge of experts in the field is applied, results in directions that can improve the efficiency of the product development cycle and control the reliability and quality of resulting products.
This appendix describes the protocol used to obtain interviews during the preliminary stage of this research project. The main layout of the interviews comprises of an introduction, questions and a debriefing.

In the introduction, the background of the research project and aims of the interviews are explained to the participants. The interview consists of several main topics guided by questions and sub-topics. In the debriefing section, the main results of the interview are summarized. The participant is also informed about closing remarks, his or her interest in the results and his or her willingness to participate in evaluation interviews at the end of the research project.

An overview of the questions used to guide in-depth interviews arranged by the main topics are described below. The questions mainly function as a guideline. Depending on the participant, freedom is exercised when seeking a specific inquiry by means of sub-topics. Questions were originally written in Dutch and have been translated into English with the intention of maintaining the Dutch meaning as much as possible.

Introduction

- During development, in what type of products are you involved?
- For how long have you been familiar with heat dissipation in electronic products?
- How long did it take you to obtain the most pertinent knowledge and methods?

Process

- In which phase of the development process is heat dissipation taken into account?
APPENDIX A. PROTOCOL USED TO INTERVIEW EXPERTS

Design freedoms

- Which problems occur most often?
  - Maximum temperature of components.
  - Temperature encasing (ergonomics).
  - Temperature outgoing airflow (ergonomics).
  - Which components are most critical?
  - Hot spots.

- Could you indicate which solutions are available for resolving these problems and at what time they are applied?
  - Positioning components on printed circuit boards.
  - Positioning of modules and printed circuit boards.
  - Conduction to the encasing.
  - Free or forced convection (fans).
  - Positioning holes in the encasing.
  - Material choice (encasing).
  - Size of the encasing.
  - Conduction to heatpipes.
  - Conduction to cooling boards.
  - Conduction to cooling fins.
  - Use of Peltier elements.

- Which aspects are an issue during detail design?
  - Have these problems already been solved during the conceptual phase?
  - What freedoms do you have when designing detail?
  - Does component choice play a significant role?
  - Placement of components on a printed circuit board.
  - Material choice of the encasing.
  - When is the (power dissipation) design released for production?
  - Do detail issues that must be improved occur after product introduction?
  - How are these problems solved?

Decision making

- Based on which conditions is a concept selected? How do you decide which design is most optimal?
– Temperature distribution.
– Maximum temperature.
– Options for improvements.
– Heat transfer coefficients.
– Material properties.
– Costs.
– Complexity.
– Development time.
– Junction temperature.
– Hot spots.

- Which means for analyzing temperature are used to assess heat dissipation in the product and why?
  – Specifications manufacturer.
  – Hand calculations (which?).
  – Handbooks, specialist literature, scientific literature.
  – Experience with comparable situations.
  – Rules of thumb (which?).
  – Software tools (licenses, internet applications or in-house development?).
  – What are the advantages and disadvantages of using these type of tools?
  – Outsourcing.

Examples from practice

- Could you describe some common situations during implementation in which power dissipation is a significant problem?
  – How many iterations occur during the design process?
  – What is the lead development time of such products?

- Can you indicate which solutions are available in resolving these problems?
- Can you indicate how you have assessed the effect of the solutions?
- Which solutions was preferred? What is the basis for this argument?

Hypothesis

Suppose you are designing a product platform for an electronic product. The functionality of the product and the criteria are known. This means that the analysis phase is
finished and you can focus on conceptual design. As a means of supporting the conceptual design, you have at your disposal several easy-to-use formulas (comparable to formulas available for calculating stress and strain in mechanics) that can be used to assess the most common situations and include the following:

- Form characteristics, such as volume and surface area.
- Material indication.
- Active versus passive cooling.
- Placement of holes in the encasing.
- Position of printed circuit boards and sub-assemblies.
- Position of components on a printed circuit board.
- Cooling fins.
- Heat pipes.
- Fans.

What effect would this have on the development process?

De-briefing

The respondents are debriefed by presenting a summary of the conversation. The participants are also asked if they have any questions regarding the interview and the processing of the results. Finally, the participants are asked about their willingness to participate in evaluation interviews planned for the end of the project.
Euler algorithm for solving state-space equation

This appendix describes an algorithm for the explicit Euler method used to compute the state-space equations described in chapter 5.

**Defining the constants**

Ta = 23; ambient temperature
Wh = 35E-3 Dh = 31E-3 Hh = 30E-3; width, depth and height for heatsource
We = 44E-3 De = 60E-3 He = 35E-3; width, depth and height for encasing
k1 = 73 k2 = 0.03 k3 = 0.2; thermal cond. heatsource (iron), air and encasing (plastic)
Le = 2E-3; encasing thickness
m1 = 106E-3 m3 = 32E-3; mass heatsource and encasing
cp1 = 0.452E3 cp2 = 1.0E3 cp3 = 2.0E3; specific heatsource, air and encasing
p2 = 1.29; air density
h = 15; heat transfer coefficient

**Computing variables**

C1 = m1 * cp1; thermal capacitance hotspot
Ve = We * De * He;
Vh = Wh * Dh * Hh;
V2 = Ve - Vh;
m2 = V2 * p2;
C2 = m2 * cp2; thermal capacitance inside air C2
C3 = m3 * cp3; thermal capacitance encasing C9
A1 = Wh * Hh;
L1 = Dh / 2;
\[ R_1 = \frac{L_1}{k_1 A_1}; \text{thermal resistor R1} \]
\[ A_2 = 2(Wh*Hh+Dh*Hh+Wh*Dh); \]
\[ R_2 = \frac{1}{h_1 A_2}; \text{thermal resistor R2} \]
\[ A_3 = 2(We*He+De*He+We*De); \]
\[ R_3 = \frac{Le}{(k_3 A_3)}; \text{thermal resistor R3} \]
\[ A_4 = 2(We*He+De*He+We*De); \]
\[ R_4 = \frac{1}{(h_4 A_4)}; \text{thermal resistor R4} \]

**Starting conditions**
\[ t = 0; \text{starting at time 0} \]
\[ dt = 0.01; \text{timestep is 1 second} \]
\[ E_1 = 0; \text{energy stored in hotspot} \]
\[ E_2 = 0; \text{energy stored in internal air} \]
\[ E_3 = 0; \text{energy stored in encasing} \]
\[ e_1 = 0; \text{temperature difference core hotspot and hotspot surface} \]
\[ e_2 = 0; \text{temperature difference hotspot surface and internal encasing} \]
\[ e_3 = 0; \text{temperature difference internal encasing and external encasing} \]
\[ e_4 = 0; \text{temperature difference external encasing and ambient} \]
\[ X = [E_1/C_1; E_2/C_2; E_3/C_3]; Y = [e_1; e_2; e_3; e_4]; \]
\[ U = [1]; \]
\[ A = [-1/(R_1*C_1) 1/(R_1*C_2) 0 1/(C_1*R_1) -(1/R_1 + 1/R_2)*(1/C_2) 1/(R_2*C_3); 0 1/(R_2*C_2) -(1/R_2 + 1/(R_3 + R_4))*(1/C_3)]; \]
\[ B = [1; 0; 0]; \]
\[ C = [1/C_1 -1/C_2 0 0 1/C_2 -1/C_3; 0 0 (R_3/(R_3 + R_4))*(1/C_3); 0 0 (R_4/(R_3 + R_4))*(1/C_3)]; \]
\[ D = [0; 0; 0; 0]; \]
\[ E = B*U; \]
\[ F = D*U; \]
\[ i = 0; \]

**Solution loop**
\[ \text{while } t < 7200; \]
\[ i = i + 1; \]
\[ X_{flux} = A*X+E; \text{derivative of X} \]
\[ Y = C*X; \]
\[ y_1(i) = Y(1); \text{writing solution to vector} \]
\[ y_2(i) = Y(2); \text{writing solution to vector} \]
\[ y_3(i) = Y(3); \text{writing solution to vector} \]
\[ y_4(i) = Y(4); \text{writing solution to vector} \]
\[ tv(i) = t; \text{writing solution to vector} \]
\[ X = X_{flux}*dt + X; \text{Euler} \]
\[ t = t + dt; \]
\[ \text{end} \]
This appendix presents the algorithm programmed in Matlab to apply a function for the unconstrained minimization of thermocouple measurements. In essence, the algorithm computes coefficients that best fit the data to the formula, in this case, a basic exponential function. The validity of the fit is calculated using Matlab by means of the least square of the deviations. Interested readers are referred to the explanation database in Matlab.

**Defining the driver**

% Driver for heat data fitting, calls objfun.m
% Joris Vergeest, Delft, 6 September 2006

```matlab
global heat1;
global tstart;
global tend;
heat1 = [1, 26.6; 301, 33.0; 601, 43.6; 901, 49.8]
tstart = 1
tend = 4
options=optimset('LargeScale', 'off');
x0 = [3, -1]
[x, fval, exitflag, output] = fminunc(@objfun, x0, options);
x, fval
```

143
Defining the function

% Function for unconstraint minimization of the
% Sum of differences squared of (F(A,D,t(i)) - V(t(i)), where V(t(i)) is
% Measured voltage (temperature) at time t(i) and F(A,D,t(i)) is a function
% Computed for t(i). A and D are x(1) and x(2), the two degrees of freedom.
% See note Temperature V1 as a function of t, 31 August 2006.

% Joris Vergeest, Delft, 31 August 2006

function f = objfun(x);
global heat1;
global tstart;
global tend;
t=heat1(:,1)*0.001;
V=heat1(:,2);
for i = tstart: tend;
Fi=x(1)+(V(i)-x(1))*exp(x(2)*(t(i)-t(1)));
d(i)=(V(i)-Fi)^2;
end
f=sum(d(tstart:tend));
Protocol used to conduct the usability experiment

This appendix contains usability experiment protocol. The experiment is subdivided into several sections, of which an overview is given in table D.1. The experiment starts with a preliminary interview in which the experience of the participants is assessed. The experiment follows with the application of the three models and methods for several sample assignments. An explanation of the models via e-mail is sent to participants several days before the experiment begins. A document giving explanations needed during the experiment’s completion is also given to the participants. The experiment finishes with a de-briefing in which the participants are asked to give their opinions of the models and fill out a closing questionnaire.

<table>
<thead>
<tr>
<th>Action</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction and preliminary questionnaire</td>
<td>5 min</td>
</tr>
<tr>
<td>Method 0: Preliminary course in heat transfer</td>
<td>15 min</td>
</tr>
<tr>
<td>Method 1: Graphic approach</td>
<td>15 min</td>
</tr>
<tr>
<td>Method 2: Numerical software program</td>
<td>15 min</td>
</tr>
<tr>
<td>Method 3: Back-of-envelope formula</td>
<td>15 min</td>
</tr>
<tr>
<td>De-briefing and closing questionnaire</td>
<td>10 min</td>
</tr>
<tr>
<td>Total time</td>
<td>75 min</td>
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</tbody>
</table>

Table D.1: Usability experiment screenplay.

Preliminary questionnaire

1. Do you have any experience or background in heat transfer? Yes □ - no □. If you answer yes, describe the type of experience in which you have been involved.
2. Have you ever made use of computational fluid dynamics (CFD) or a finite element analysis (FEA) to calculate temperature? Yes ☐ - no ☐. If you answer yes, please describe the program.

3. Have you ever been involved in the design process for (electronic) product(s) that later developed heat problems? Yes ☐ - no ☐. If you answer yes, please describe the type of product(s).

4. How would you calculate/analyze temperature in a product?

Assignment

During the completion of assignments, participants are given an explanation of the application of the three models, including an explanation on how to use resistor networks to calculate temperature differences. Several tables and figures are also given, along with data on heat transfer coefficients and material properties. Then, participants are asked to apply the models to an electronic product. As an example, the contents of an AC-DC adapter are shown. The assignment is formulated as follows: Before you are the contents of an AC-DC adapter. It dissipates four watts of electrical power (q), resulting in a rise in temperature in the hotspot (the coil). You have been asked to design the encasing. The design must fulfill the following criteria:

- Maximum allowed hotspot temperature of 70°C
- Maximum allowed encasing dimensions of 60mm × 60mm × 60mm

Please think out loud so that I can follow your design process. Good luck!

De-briefing questionnaire

Question 01 How easy or difficult is it to understand the models? 1 = easy 5 = difficult

<table>
<thead>
<tr>
<th>Model 0</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
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Question 02 How well does the method deliver desired results? 1 = Good results 5 = Bad results

<table>
<thead>
<tr>
<th>Model 0</th>
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<th>Model 3</th>
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Question 03 Can you arrange the models according to ease of use?
Question 04  Would you use the models for completing specific design cases when they become fully-operational and matched to specific design cases?

<table>
<thead>
<tr>
<th>Model 0</th>
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<tr>
<td>Yes No</td>
<td>Yes No</td>
<td>Yes No</td>
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</table>

Question 05  Do you think that this method is easy to remember and use in a future design situation?

<table>
<thead>
<tr>
<th>Model 0</th>
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<tr>
<td>Yes No</td>
<td>Yes No</td>
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Question 06  Does this model easily correct errors or incorrect design decisions for a conceptual design?

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<th>Model 0</th>
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<tr>
<td>Yes No</td>
<td>Yes No</td>
<td>Yes No</td>
<td>Yes No</td>
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</table>

Question 07  Can this method cause errors or incorrect design decisions for a design or have any other negative effects? If yes, what types of errors or negative effects would you anticipate?

<table>
<thead>
<tr>
<th>Model 0</th>
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<th>Model 2</th>
<th>Model 3</th>
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<tr>
<td>Yes No</td>
<td>Yes No</td>
<td>Yes No</td>
<td>Yes No</td>
</tr>
</tbody>
</table>

Question 08  Would you still use other methods during conceptual design to prevent errors? Yes □ - no □. If yes, which methods would you use?

Question 09  What do you think about the time the models take to properly apply? 1 = little amount of time 5 = much time

<table>
<thead>
<tr>
<th>Model 0</th>
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</table>

Question 10  The method results in better product cooling concepts than my own method. 1 = much better cooling concept 5 = worse cooling concept
APPENDIX D. PROTOCOL USED TO CONDUCT THE USABILITY EXPERIMENT

<table>
<thead>
<tr>
<th>Model 0</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
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<tbody>
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<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
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</tbody>
</table>

Question 11 Can you arrange the models according to the reliability of the obtained answer?

<table>
<thead>
<tr>
<th>Reliable</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreliable</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Question 12 Can you arrange the models according to their accuracy in estimating temperature?

<table>
<thead>
<tr>
<th>Best quality</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
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</table>

Question 13 What is the advantage of using models (models 1 - 3) compared to the standard method of modeling (model 0)?

Question 14 Do you think that models 1 - 3 work well independently or would a combination work better?

Question 15 Which model works best in a realistic design assignment and which type of products would achieve the most benefit from implementation?

Question 16 Would you use one or more of these methods? Yes □ - no □. Why?

Question 17 For which type of products or design situations do you believe these models most appropriate? Please provide examples.

Question 18 Can you give examples for when you could have used the presented models?

Question 19 Can this model be helpful in communication with regards to design decisions made between mechanical, hardware and software engineers?

Question 20 Can the models prevent problems in the later stages of the design process?

Question 21 What is the downside of using the presented models?

Question 22 Can you think of any means for improving the use of the models?

Question 23 Do you have any suggestions on how to improve the models?


# Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Surface area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$C$</td>
<td>Thermal capacitance</td>
<td>$J/K$</td>
</tr>
<tr>
<td>$c$</td>
<td>Constant</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat</td>
<td>$J/(kg \cdot K)$</td>
</tr>
<tr>
<td>$F_{1,2}$</td>
<td>View factor</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity constant</td>
<td>$m/s^2$</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient</td>
<td>$W/(m^2 \cdot K)$</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Convection heat transfer coefficient</td>
<td>$W/(m^2 \cdot K)$</td>
</tr>
<tr>
<td>$h_r$</td>
<td>Radiation heat transfer coefficient</td>
<td>$W/(m^2 \cdot K)$</td>
</tr>
<tr>
<td>$h_{tot}$</td>
<td>Total heat transfer coefficient</td>
<td>$W/(m^2 \cdot K)$</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
<td>$A$</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
<td>$W/(m \cdot K)$</td>
</tr>
<tr>
<td>$k_{air}$</td>
<td>Thermal conductivity of air</td>
<td>$W/(m \cdot K)$</td>
</tr>
<tr>
<td>$k_f$</td>
<td>Thermal conductivity of fluidum</td>
<td>$W/(m \cdot K)$</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Specific dimension</td>
<td>$m$</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
<td>$kg$</td>
</tr>
<tr>
<td>$q$</td>
<td>Power dissipation</td>
<td>$W$</td>
</tr>
<tr>
<td>$R$</td>
<td>Electric resistance</td>
<td>$(kg \cdot m^2)/(A^2 \cdot s^3)$</td>
</tr>
<tr>
<td>$\delta T$</td>
<td>Temperature differential</td>
<td>$K$</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference</td>
<td>$K$</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature</td>
<td>$K$ or °C</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Encasing temperature</td>
<td>$K$ or °C</td>
</tr>
<tr>
<td>$T_h$</td>
<td>Hot spot temperature</td>
<td>$K$ or °C</td>
</tr>
</tbody>
</table>
\( T_s \)  
Surface temperature  
\( K \) or \(^\circ\)C

\( T_f \)  
Fluid temperature  
\( K \) or \(^\circ\)C

\( T_{av} \)  
Average temperature  
\( K \) or \(^\circ\)C

\( T_{1,2} \)  
Radiating surface temperature  
\( K \) or \(^\circ\)C

\( V \)  
Voltage  
\((kg \cdot m^2)/(A \cdot s^3)\)

\( x \)  
Distance  
\( m \)

\( X \)  
Time constant  
\( s \)

\( \beta_{air} \)  
Temperature coeff. of volume exp.  
\( 1/K \)

\( \delta x \)  
Distance differential  
\( m \)

\( \epsilon \)  
Emissivity of radiating surface  
\textit{dimensionless}

\( \mu_{air} \)  
Absolute viscosity  
\((N \cdot s)/m^2\)

\( \rho_{air} \)  
Density air  
\( kg/m^3 \)

\( \sigma \)  
Stefan-Boltzmann constant  
\( 5.67 \cdot 10^{-8} \ W/(m^2 \cdot K^4) \)

\( \theta \)  
Thermal resistance  
\( K/W \)

\( \theta_c \)  
Convective thermal resistance  
\( K/W \)

\( \theta_k \)  
Conductive thermal resistance  
\( K/W \)

\( \theta_r \)  
Radiative thermal resistance  
\( K/W \)

\( \nu_{air} \)  
Kinematic viscosity  
\( m^2/s \)

\( Gr \)  
Grashof number  
\textit{dimensionless} \((L^3 \cdot \rho^2 \cdot \beta \cdot g \cdot \Delta T)/\mu^2\)

\( Nu \)  
Nusselt number  
\textit{dimensionless} \((h_c \cdot L_c)/k_f\)

\( Pr \)  
Prandtl number  
\textit{dimensionless} \((c_p \cdot \mu)/k\)

\( Ra \)  
Rayleigh number  
\textit{dimensionless} \((Gr \cdot Pr)\)
Present thermal design tools and methods insufficiently support the development of structural concepts engaged by typical practicing designers. Research described in this thesis identifies the main thermal design problems in practice. In addition, models and methods are developed that support an efficient conceptual thermal design process, resulting in higher quality products. Finally, the applicability, efficiency and quality of applying the models in design is evaluated by means of experiments and interviews.

In the preliminary stage of this research, an overview is given of the practical problems encountering thermal design in practice. This resulted from an overview of the tools and methods described in literature and a series of semi-structured interviews with practicing designers. This preliminary research results in three main conclusions. First, many designers are unfamiliar with heat transfer and thermal design theories. Such designers lack the basic knowledge to make conceptual design choices and evaluate how important temperature will be during design. Second, evaluating structural concepts for heat flow and temperature development is not supported by a standard approach. Finally, temperature measurements for mock-ups and functional models are crucial in practical thermal design in order to find reliable heat transfer coefficients.

Based on these results, three “conceptual” approaches have been developed that address one of the three problems. Each approach consists of a thermal design model and method for applying the model in a design situation. Model 1 is a chart, combined with a rule-of-thumb, that can be used as a risk assessment tool by a designer who has no knowledge of heat transfer or thermal design. Model 2 is a software tool that can be used to compute the heat path for structural concepts and is useful for rough temperature estimation in an electronic product. Model 3 is a theoretical formula that can be used to calculate the total transient behavior in a device and can be expanded by applying more detail. Because the model is theoretically derived, the designer can easily adjust the formula to fit a specific situation. Boundary conditions, thermal resistance and thermal capacitance are derived from measurements. The result is a semi-empirical model that is
valid for a specific application and can be used to evaluate design changes.

The three models and application methods have been evaluated by means of experiments using novice designers and interviews with practicing design engineers who all have experience in the design of electronic products with heat problems. The evaluation study shows that thermal design during the conceptual phase can be improved through several means. Designers can use the graph and rule of thumb embedded in model 1. By using this model, the most important structural concept decision regarding thermal design can be made: Should active or passive cooling be used? In addition, the designer obtains some idea of the importance of the role that thermal design will play in the development process. If the design is critical, the designer can choose to contact a thermal design specialist during the beginning stages to help define an optimal structural concept. This saves time and will most likely result in a design that is less vulnerable to after-defect solutions. A second step should including having the designer gain some background in heat transfer so that the concepts behind models 2 and 3 can be understood and applied. For this, it is necessary to expand these concepts into a various range of solutions that will evaluate the heat path for several structural concepts. The approach is comparable to that used in mechanical design, which has been successfully applied for many years. However, before entering this stage, a tremendous amount of experience data and modeling must be completed.

The scientific relevance of this thesis does not just propose and develop models and methods that can improve the generation of structural concepts in early design phases. It also shows, for the first time, the application of an approach that combines scientific literature and interviews with designers from the field with thermal design research. Such an approach, in which the systematic use of available theory and knowledge of experts in the field, results in suggestions that can lessen the time needed to complete the product development cycle by several weeks and control the reliability and quality of resulting products.
De huidige hulpmiddelen en methoden om het thermisch ontwerp van elektronische producten uit te voeren ondersteunen onvoldoende de ontwikkeling van structurele concepten zoals gebruikelijk is bij ontwerpers uit de praktijk. Het onderzoek dat in deze thesis is omschreven achterhaalt de belangrijkste thermische ontwerpproblemen uit de praktijk. Hier aan toevoegend worden modellen en methoden ontwikkeld die een efficiënt conceptueel thermisch ontwerpproces ondersteunen wat resulteert in een hogere kwaliteit van eindproducten. Ten slotte is de bruikbaarheid, efficiëntie en kwaliteit van de toepassing van de modellen in het ontwerpen geëvalueerd door middel van experimenten en interviews.

In de beginfase van dit onderzoek is een overzicht gemaakt van de praktische problemen van het thermische ontwerp in de praktijk. Een overzicht van de beschikbare hulpmiddelen en methoden uit de literatuur en diepe interviews met ontwerpers uit de praktijk resulteerde in drie hoofdconclusies. Om te beginnen zijn veel industrieel ontwerpers niet bekend met warmteoverdracht theorieën en thermisch ontwerptheorieën. Deze ontwerpers ontbreekt de basiskennis om conceptuele ontwerpkeuzes te kunnen maken en om te evalueren hoe belangrijk temperatuur wordt in het ontwerp. Ten tweede wordt de evaluatie van structurele concepten op warmtestroom en temperatuursontwikkeling niet ondersteund door een standaard aanpak. Ten slotte is het meten van temperatuursontwikkeling in proefopstellingen en functionele modellen cruciaal om betrouwbare warmteoverdrachtscoëfficiënten te achterhalen.

Op basis van deze resultaten zijn drie ‘concept’ benaderingen ontwikkeld die ieder ingaan op een van de drie problemen. Elke benadering omvat een thermisch ontwerpmodel en een methode om het model toe te passen in een ontwerpsituatie. Model 1 is een grafiek gecombineerd met een vuistregel en kan worden gebruikt als een risicoadicatie door de ontwerper die geen of weinig kennis heeft van warmteoverdracht en thermisch ontwerpen. Model 2 is een computer programma dat het warmtepad in structurele concepten kan doorrekenen en is bruikbaar voor een globale inschatting van de temperaturen.
in een elektronisch product. Model 3 is een theoretische formule die kan worden gebruikt voor de inschatting van het tijdsafhankelijke (transiënt) gedrag in een product. Omdat het model theoretisch is afgeleid kan de ontwerper de formule aanpassen naar een specifieke situatie. De warmteweerstand en totale warmtecapaciteit van het product dienen te worden achterhaald uit metingen aan een functioneel model of thermische proefopstellingen. Het resultaat is een semi-empirisch model dat gecalibreerd is op de specifieke toepassing en dat kan worden gebruikt om het effect van ontwerperveranderingen te voorspellen.

De drie modellen en toepassingsmethoden zijn geëvalueerd door middel van experimenten met beginnende ontwerpers en door middel van interviews met ervaren ontwerpers die allen ervaren zijn in het omgaan met warmteproblematiek. De evaluatiestudie laat zien dat het thermische ontwerp in de conceptfase kan worden geoptimaliseerd op verschillende manieren. Ontwerpers kunnen de grafiek en vuistregel van model 1 gebruiken om zo een belangrijke thermisch ontwerpbeslissing ten aanzien van het structurele concept te maken. Deze beslissing is: actieve of passieve koeling. Tevens krijgt de ontwerper hiermee een beeld over hoe belangrijk thermisch ontwerpen in het product ontwikkelingsproject zal zijn. In het geval het ontwerp kritisch is zal de ontwerper kunnen besluiten om een thermisch ontwerpspecialist bij het project te betrekken om een optimaal koelingconcept te definiëren. Dit scheelt tijd en resulteert hoogstwaarschijnlijk in een ontwerp dat minder gevoelig is voor oplapoplossingen. Een tweede stap voor de ontwerper zal zijn het opdoen van kennis op het gebied van warmteoverdracht zodat deze het principe achter model 2 en model 3 kan begrijpen en toepassen. Hiertoe zal het nodig zijn dat deze twee conceptrichtingen worden uitgewerkt voor een reeks standaard oplossingen om het warmtepad in een product te kunnen berekenen. Deze aanpak is vergelijkbaar met de manier waarop de formules voor spanning en rek al jaren succesvol worden toegepast in de mechanica. Echter, voor dit doel is bereikt zal nog een grote hoeveelheid aan ervaringsgegevens en modellering moeten worden onderzocht.

De wetenschappelijke relevantie van dit onderzoek is niet enkel het ontwikkelen van een model en toepassingsmethode ter verbetering van het bedenken van structurele concepten in de beginfase van het ontwerpen. Het laat echter ook voor de eerste keer op het gebied van thermisch ontwerp een aanpak zien waarin literatuur wordt gecombineerd met interviews met ontwerpers uit de praktijk. Ook het evalueren van modellen en methoden van toepassing in een gebruikersstudie is, voor zover bekend, voor het eerst op dit vakgebied toegepast. Het is gebleken dat een aanpak waar systematisch wordt omgaan met beschikbare theorie en kennis van ontwerpexperts uit de praktijk, resulteert in richtingen die de efficiëntie van het product ontwikkeltraject kan optimaliseren en de betrouwbaarheid en kwaliteit van het resulterende product kan verbeteren.
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Ruben Strijk was born in Nijmegen, The Netherlands, on the 5th of August, 1975. He obtained his MAVO, HAVO and VWO exams in 1991, 1993 and 1995, respectively. He graduated from the Delft University of Technology in Industrial Design Engineering. During his studies, he concentrated on design for sustainability and followed his internship by working for several months in the design agency, KIEM. His graduation project focused on the design of a direct methanol fuel cell system and was completed for the Energy Research Centre of The Netherlands (ECN). After completing his study in 2002, he began working as a designer at Koppert Biological Systems, b.v, a company focused on the natural control of pests and pollinating greenhouse crops. Here, he worked on various projects involving production logistics, assembly, manufacturing and packaging. In 2003, he began his work as a PhD researcher for the Faculty of Industrial Design Engineering at Delft University of Technology.

In his spare time, he plays trumpet and guitar and practices Goju Ryu karate-do.