THERMAL DESIGN USING SYSTEM MODELING TO PREVENT LOW-TEMPERATURE BURN INJURIES DURING UTILIZATION STAGE OF PORTABLE ELETRONIC PRODUCTS

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Abstract

During utilization stage of portable electronic products such as smartphones and digital cameras, risk of low-temperature burn injuries to a user by temperature rise on product surface has become a growing concern. Temperature rise incidents are increasing because of the demands for smaller- and higher-performance products. Many functions of electronic products are realized by software. Because components including software and hardware interact complicatedly, verification for thermal quality tends to be performed after integration of software and hardware in the late stage of the development. Therefore the thermal problem may cause fatal iterative work at the development. In addition, not only product development, but also production and support affect temperature rises during end-user product utilization, thermal design must be considered through product lifecycles.

To address the concerns of low-temperature burn injuries and fatal iterative work, the author proposes a system modeling for estimating a product's thermal quality using its design parameters. A portable electronic product consists of modules such as software, electrical parts and mechanical structures, which are developed in a distributed design environment. A system model describes behaviors of heat generation and transfer according to the states of the electrical parts that perform functions when in use. This dissertation clarifies the interactions of modules that affect temperature rise, by applying a modeling system to a portable electronic product. The author also proposes a method to manage the factors that affect the thermal quality during module designs to prevent fatal iterative work. In addition, this system model is used to understand heat generation condition in the development, production and support stages of the product lifecycle.

This dissertation consists of five chapters. In Chapter 1, the background and purpose of this research are described. Chapter 2 describes the architecture design of a portable electronic product in thermal design view. A system model is developed to describe behaviors of heat generation and transfer. To understand the possibility leading to low-temperature burn injuries, a product's thermal quality is estimated with the modules' design parameters using thermal simulations based on the system behaviors. After architecture candidates of the product are defined, boundary conditions between modules are distributed to the designs of individual modules as initial target values (ITVs). Using ITVs, modules are efficiently designed and verified to satisfy the thermal quality of the example product. In case an inconsistency is found during the module

design, another combination of ITVs is investigated, developed, and updated to satisfy the product thermal quality requirements. A multiple-domain matrix (MDM) is used to visualize the system elements and the above-mentioned module interactions in thermal design view. By describing the thermal simulation result with the MDM, the effects of system behaviors and structure on a product's thermal quality can be presented quantitatively.

In Chapter 3, thermal designs using system modeling are applied in the product development and support stages of the product lifecycle. Activities that describe thermal behaviors are decomposed to be allocated to the relevant system component. During the development stage, the thermal design specifications of a portable electronic product are derived using thermal simulation. Because the architecture candidates that are traceable to the system model are defined, the most appropriate candidate can be selected. The thermal simulation based on the system model is applied for the design changes that are expected to degrade the product's thermal quality by adjusting design parameters of the modules. During the support stage, a product's thermal quality may degrade due to software changes such as operating system (OS) updates. This dissertation describes the thermal design method to prepare countermeasures against further temperature rise caused by software changes. Since the expected behaviors are reflected in the system model, an assessment of countermeasure alternatives can be effectively performed when the thermal quality is degraded.

Chapter 4 applies the system model in the production stage. To address concerns that the variability of leakage current effect of a semiconductor processor may cause further temperature rises, the leakage current effect is included as behavior in the system model. Then, the thermal simulation developed for architecture design is employed to determine the allowable range of variability in the leakage current. Components that cause quality degradation can therefore be screened for compliance with this range before implementation of the components. Chapter 5 concludes this dissertation with a discussion of possible future work.

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Abbreviations

CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CMOS	Complementary Metal-Oxide Semiconductor
DMM	Domain Mapping Matrix
DSM	Design Structure Matrix
DSP	Digital Signal Processor
EMC	Electromagnetic Compatibility
ESD	Electrostatic Discharge
HD	High Definition
ITVs	Initial Target Values
IC	Integrated Circuit
ICT	Information and Communication Technology
MDM	Multiple-Domain Matrix
OS	Operating System
PC	Personal Computer
PWB	Printed Wiring Board
SysML	System Modeling Language
TCM	Thermal Coupling Matrix
TIM	Thermal Interface Material

Nomenclature

A_{s_i}	Surface area
C_l	Load capacitance of a semiconductor
F	Operating voltage frequency
dT	Temperature rise
h	Heat transfer coefficient
I_{ls}	Subthreshold leakage current
k	Boltzmann's constant k
l	length
n	Subthreshold coefficient
P_{chg}	Power consumption by battery charging
P_{per}	Power consumption of peripheral components
Q	Heat dissipation of a product
$\mathrm{Q_{chg}}$	Heat dissipation by the voltage conversion loss
Q_p	Heat dissipation of a semiconductor processor
Q_{per}	Heat dissipation of peripheral components
Q_{ps}	Heat dissipation of a power supply unit
$Q_{\_\mathrm{i}}$	Heat transfer
R_{s_i}	Equivalent thermal resistance
R_{mec}	Thermal resistance of mechanical structures
St_{chg}	State of battery charging
St_{per}	State of peripherals
t	Thickness
T_{amb}	Ambient temperature
T_{pwb}	Temperature of a PWB
T_{max}	Maximum temperature
T_p	Temperature of a semiconductor processor
T_s	Surface temperature
Ut	Temperature voltage
V_{dd}	Operating voltage
V_s	Supply voltage
V_{th}	Threshold voltage
w	Width
λ_i	Thermal conductivity

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Chapter 1

Introduction

1.1 Research background

1.1.1 Thermal problems in portable electronic products

The risks of low-temperature burn injuries during utilization of a portable electronic product have already been reported. Portable electronic products can heat up considerably, especially when the product handles content-rich applications such as video games or HD video recordings (Consumer Reports 2012; Qualcomm 2012). Each component of the product has an optimum operating temperature range. Temperatures exceeding this range may damage the product. Moreover, high enclosure temperatures induce low-temperature burn injuries if the user touches the product. Even temperatures perceived as relatively comfortable to the touch may cause burn injuries when the contact is maintained for prolonged periods. Low-temperature burn injuries caused using laptop PCs have been reported to call attention to this issue (National Institute of Technology and Evaluation 2015). In addition, non-IT products can cause low-temperature burn injuries during the utilization. For example, the possibility of low-temperature burn injuries while shooting videos with digital video camcorders was reported by a manufacture (Canon 2012). However the heat spot of a camera is on the opposite side of its grip; nevertheless, some users may use both hands during shooting. In that case, there is a possibility of contacting the heat spot. Although the possibility of touching the heat spot was less, the manufacture was still concerned about the thermal problem.

The number of inquiries into smartphone thermal problems, in the form of consumer complaints, increased between the years 2009 and 2012 (National Consumer Affairs Center of Japan 2014) as shown in Figure 1.1 Both the number of inquiries and that of harmful incidents have rapidly increased since 2009. At the same time, there are other trends that many consider to be the causes of the accelerating temperature rise incidents reported in smartphone products. There is a trend of thickness of a typical smartphone product, as shown in Figure 1.2, which increases temperature rise incidences because of decreased product surface areas from which heat is dissipated and increased difficulties in the areas of heat spreading and thermal conductance with respect to the materials installed in the product.

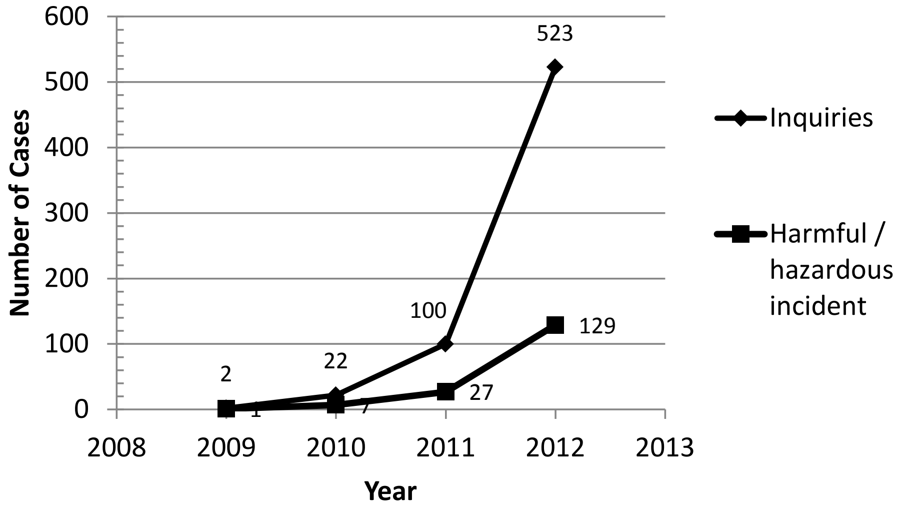


Figure 1.1 Inquiries into smartphone thermal problems (National Consumer Affairs Center of Japan, 2014)

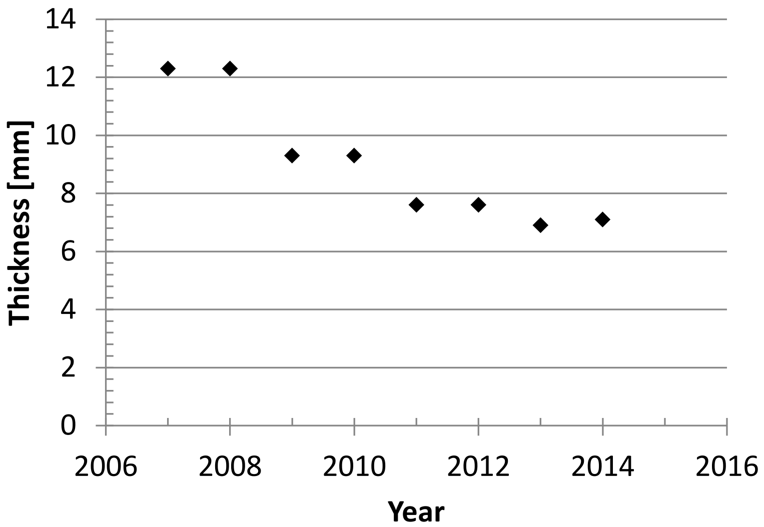


Figure 1.2 Graph indicating smartphone thickness

In addition, it is assumed that the data processing performance is being further increased, causing increases in power consumption. As shown in Figure 1.3, the semiconductor fabrication process is being miniaturized. The processor, one of the semiconductor components, is usually costlier than other electrical parts. Miniaturization of the semiconductor components contributes toward efficient mass production, which reduces the fabrication cost of each component. It also contributes to the integration of several functions, gathering large-scale circuits into one semiconductor component to achieve higher performances. However, miniaturization increases leakage power (Sekar 2013). Leakage current depends on temperature, and therefore, increases with temperature during product operation. The thermal design of electronic products has become increasingly complicated owing to this leakage current characteristic and the variation in semiconductors introduced during the production stage. During the electronic product development, increases and variations in the leakage currents of processors are difficult to predict prior to production. This unpredictable increment in current may cause higher temperature and degradation of the product quality.

However, semiconductors, including the central processing unit (CPU) and system-on-chip components, in smartphones consume very little power in the idle mode; it is the power dissipation during prolonged use that must be suppressed to prevent temperature rises. Semiconductors exceed their recommended operating temperature range when run at their maximum frequency for a long period (Benson 2014). The software in the operating system (OS) controls the states of the semiconductors to limit the operating frequencies during high load use cases such as video recording, playing games, or streaming media.

In general, portable electronic products are made of several layers of modules. Figure 1.4 shows the hardware components of a typical smartphone, which include a display, a printed wiring board (PWB), and a battery. The mechanical structures include an enclosure. A semiconductor processor is mounted on a PWB. Figure 1.5 shows a typical layout of these components and illustrates the heat transfer in a cross-sectional view. The composition is quite similar to that of other portable electronic products such as digital cameras or portable video game players.

As shown in Figure 1.6, which illustrates conventional thermal design measures relevant to the temperature rise mechanism, several activities increase the risk of low-temperature burn injuries. First, a semiconductor processor runs a software algorithm. Then, heat is generated in the processor and transferred to other components. The heat transfer causes a temperature rise on the enclosure surface, inducing the risk of a low-temperature burn injury.

To reduce or eliminate low-temperature burn injuries, the various measures shown in Figure 1.6 are applied to a product's thermal design, such as modification of the component layout and installation of thermal conductive devices including thermal interface materials (TIM) and heat spreading devices (Figure 1.5). These measures related to mechanical design approach are commonly applied to moderate the temperature distribution. However, when mechanical structures spread heat, the heat-spreading capacity is constrained by the product size. Other measures related to electrical and software design approaches are also applied in the thermal design of portable electronic products. Power consumption reduction techniques are employed to eliminate redundant computations. Control of semiconductor states during operation is also employed to limit heat dissipation. It has become increasingly difficult to satisfy the design requirements, including thermal properties, of portable electronic products during development. Because the trend of further increasing temperature has reduced the thermal design margins for unexpected design changes, it is necessary to predict thermal qualities in cooperation with software and hardware designs to eliminate low-temperature burn injuries.

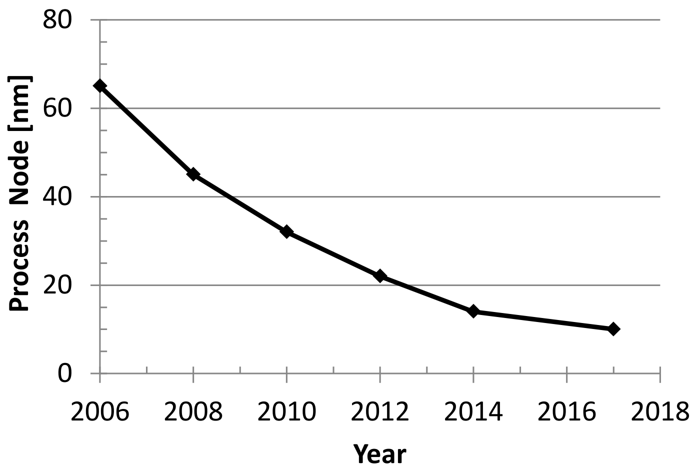


Figure 1.3 Miniaturization trend of semiconductor components

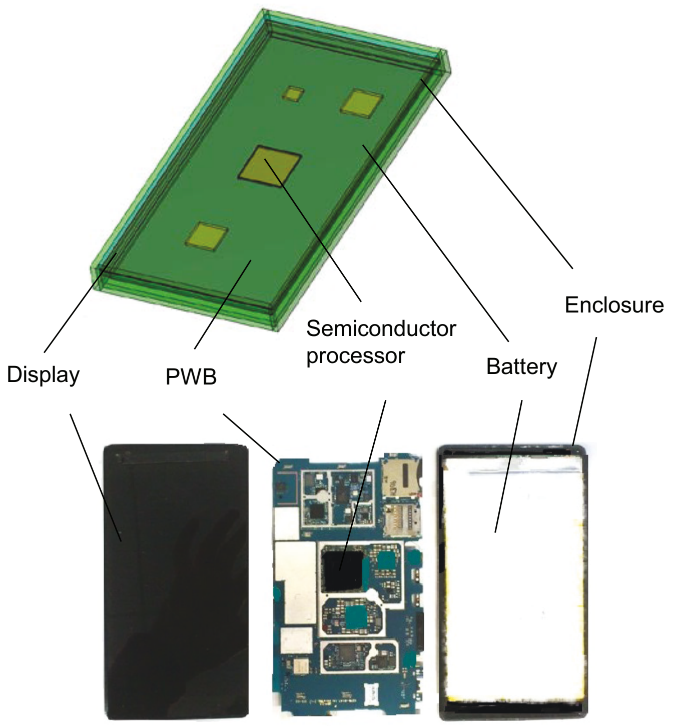


Figure 1.4 Typical component layout of a smartphone

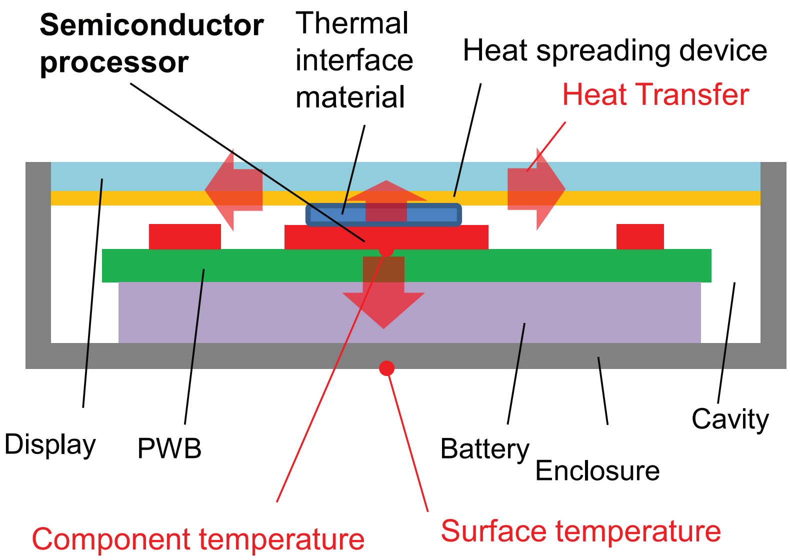


Figure 1.5 Cross-sectional view of a typical component layout and heat transfer of a smartphone

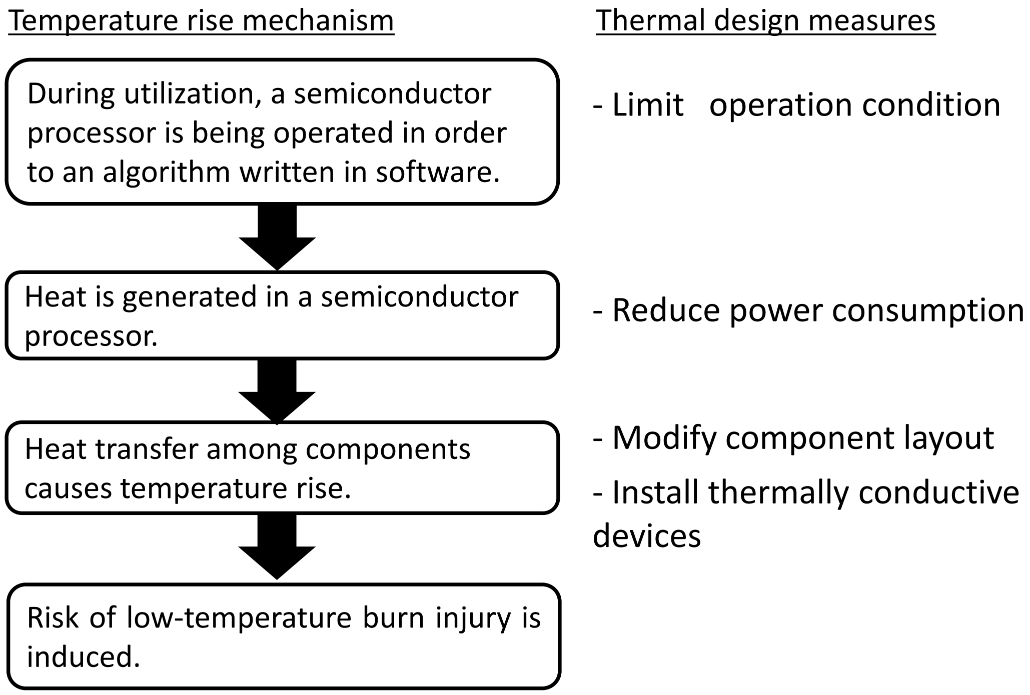


Figure 1.6 Conventional thermal design for temperature rise of a portable electronic product

1.1.2 Complexity in thermal design

Complexity during product development is amplified by the number of attributes in each product category. Table 1.1 shows the attributes of four product categories. The attributes include market volume, development period, structural complexity, and use cases. In the table, the professional electronics category includes broadcasting, medical, and telecommunication equipment. Consumer electronic products include the portable electronic products covered in this dissertation, such as smartphones, tablets, digital cameras, portable video game players, and small laptops. A comparison of consumer electronic products with other product categories shows that the development and production occurs within a very short period despite their large production volume. However, consumer electronic products generally comprise fewer components than products in other categories, which is important since the variability in each component's characteristics can affect the quality of a large number of produced units. It is therefore necessary to reduce this variability despite the short production period.

Table 1.1 Attributes of the four product categories

	Market Volume (#unit/year)	**Development period (#year)**	**Structural Complexity (#parts)**	**Use case (#application)**
Aerospace	Small	Long	Large	Small
Automotive	Medium	Long	Large	Small
Professional Electronics	Small	Medium	Medium	Small
Consumer Electronics	Large	Short	Small	Large

Table 1.2 shows examples of user requirements for portable products. Gebauer et al. (2008) found that quality characteristics including functionality, portability, performance, and usability are highly valued by users of portable electronic products such as smartphones and laptops. The product size limits portability. While processing speed affects performance, in many portable electronic products, it is designed to be limited to prevent additional temperature rises under high-temperature conditions. Thermal design during product development must consider the trade-off between portability and performance. Companies that develop or sell products are responsible for their product's quality, which includes its thermal quality, to prevent low-temperature burn injuries during utilization. Because portable electronics products are touched by users for prolonged periods, their thermal quality must be satisfied considering human contact. In addition, Falaki et al. (2010) studied the variation in smartphone uses by different users. Selection of test conditions, as well as the availability of such tests, is also considered in product quality assurance. Because product design depends on the business model and product features (Ulrich and Eppinger 2007), thermal design is a fundamental technology that is implemented in different ways.

Table 1.2 Examples of user requirements for portable products (Gebauer et al. 2008)

Factor	Examples
Functionality	Voice call, Messaging, Camera
Portability	Dimensions, Weight
Performance	Stability, Battery life, Processing speed
Usability	Display, Keyboard, Ease of use, Sound
Network connectivity	Network access, Near Field Communication

As shown in Table 1.3, which describes the relation between quality characteristic and technological disciplines, thermal quality is important in software, electrical, and mechanical technological disciplines. Verification of a product's thermal quality requires that the modules used in each of these technological disciplines are integrated. A design structure matrix (DSM), given in Figure 1.7, describes the design work flow of a portable electronic product. As shown in the matrix, the modules that constitute the product are designed at distributed sites or different enterprises regardless of the architecture in question. The design specifications of the modules are distributed to each module design after concept design. Some iterative work is planned to occur during module design. Then, modules are integrated and verified in sequence. However, their electromagnetic compatibility (EMC) and other quality characteristics can be verified with electrical parts, mechanical structures, and thermal design targets for all modules that include software, electrical parts, and mechanical structures. Therefore, verification of the thermal quality of a product is difficult in the early development stages. In case a thermal problem is found during verification in the late development stages, carrying out iterative work will cause deviations from the development schedule. If the problem is related to interactions between different technological disciplines, iterative work may affect not only one module design but also the design of the whole product.

To include the possibility of iterative work during the development stage, the thermal design must be considered during the various stages of a product lifecycle. As shown in Figure 1.8, the modules are then implemented or fabricated with different pre-planned timings. In general, electrical parts such as semiconductors, displays, and cameras take longer to fabricate than mechanical structures. Software is installed onto hardware, which consists of electrical parts and mechanical structures, after some parts of the hardware have been integrated. In addition, the relations between the organizations who participate in product development are often complicated. Many components of a product are designed by different organizations based on different disciplines or stages of the product lifecycle. Some of these organizations are often different enterprises. Therefore, lack of communication between design groups is also a concern during product development. It is difficult to comprehend the effect that each design parameter of the various components will have on the final product quality. The impact of the design decisions cannot be simply estimated. Furthermore, the whole product system must be considered by taking into account various factors such as product cost, performance, manufacturability, safety, disposability, regulatory compliance, usability, maintainability, and overall quality (Siemens 2015).

Table 1.3 Relations between quality characteristics and technological disciplines

	Software	**Electrical**	**Mechanical**
Thermal	X	X	X
EMC (Electromagnetic compatibility)		X	X
ESD (Electrostatic discharge)		X	X
Corrosion		X	X
Signal Intensity		X	
Structural Strength			X

				1. Product		2. Module										3. Product	
						Software			Electrical Parts				Mechanical Structures				
				a	b	c	d	e	f	g	h	i	j	k	l	m	n
1. Product		a	Product Planning		o												
		b	Concept Design w/o Architecture Definition	o		X			X				X			X	X
2. Module	Software	c	Software Functional Design		o		o	X								X	X
		d	Coding/Implementation and Test			o		o								X	X
		e	Verification with Electrical Parts				o				o						
	Electrical Parts	f	Floor Planning		o					o	X	X				X	X
		g	Detail Design						o		o	o				X	X
		h	Fabrication and Test (Signal Intensity)							o		o					
		i	Verification with Mechanical Structure (EMC, ESD, etc.)								o				o		
	Mechanical Structures	j	Component Layout		o									o	X	X	X
		k	Detail Design										o		o	X	X
		l	Fabrication and Test (Structural Strength)											o			
3. Product		m	Integration and Verification (Thermal, etc.)		o			o				o			o		o
		n	Validation		o											o	

Distributed design of modules

O: Planned Process, X: Undesirable Iteration, X: Fatal Iteration

Figure 1.7 DSM of the design process

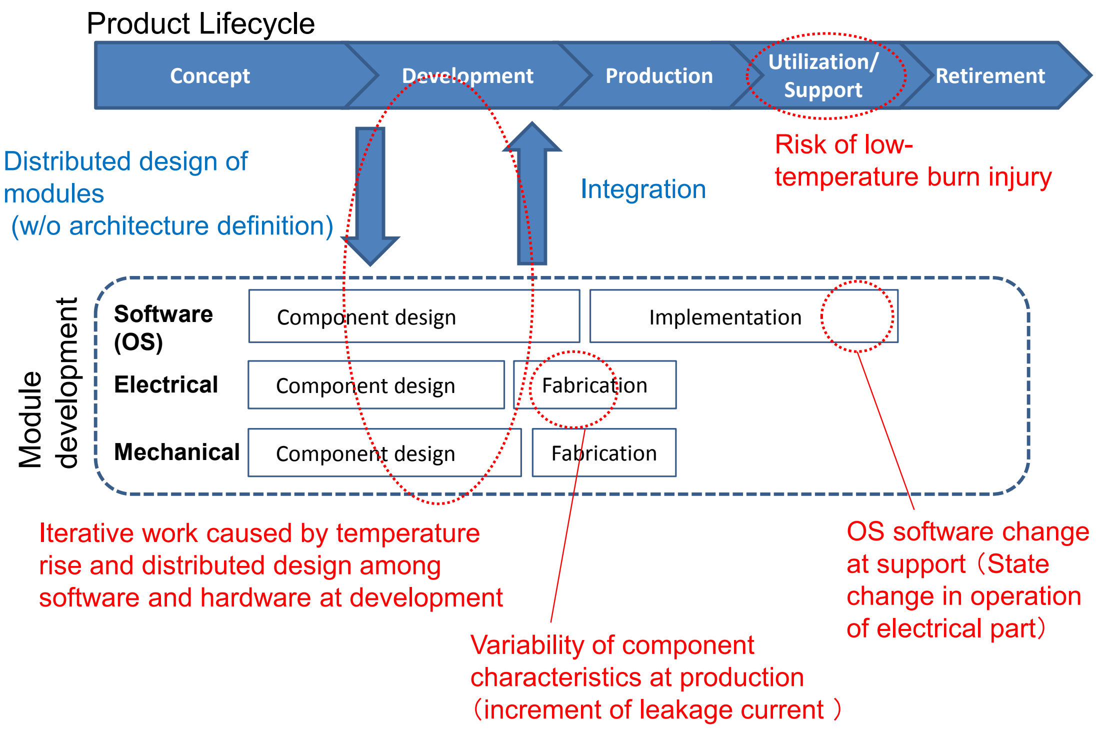


Figure 1.8 Thermal problems in the product lifecycle

Another concern in thermal design is the change in heat generation conditions after the product development is completed. During the production stage, variability in component characteristics affects the quality of several produced units. It is necessary to reduce the variability earlier, after only a short period of production. This dissertation proposes to use system modeling to cope with this specific production issue. Thermal designs of electronic products have become increasingly complicated as leakage currents are increasing, causing higher temperatures, and because of the variability.

To prevent the degradation of a product's quality that is caused by the uncertain variability in its component characteristics, applications of both robust design and numerical analysis have been explored to determine the factors that affect these characteristics (Miyazaki 2013, Katagiri and Toi 2014). Penetration of information and communication technology (ICT) into manufacturing is referred to as "Industrie 4.0." This process increases the efficiencies of collaborations within or outside fabrication plants to improve productivity, reliability, and flexibility (Ministry of Economy 2015). To decrease the variability in component characteristics, autonomous control systems based on robotics and sensing technologies are introduced in the assembly process (Matue et al. 2015). Simulations are employed during product design to increase the flexibility of a production system (Kagermann et al. 2013). Simulation models based on system models are used in architecture exploration in the early stages of product design.

Additionally, OS software updates during support cause state changes in the operation of electrical parts. Post-purchase installation of software, including applications and new OSs, now constitute the bulk of product variation (Kuusela 2012). As shown in Figure 1.9, an official version of Android OS is released several times a year, which means that new OS updates occur during usage, especially if the product is being used for many years. In 2013, the number of available Android applications had already reached one million (Google 2013). However, verification resources and measures to decrease temperature rises are limited after development. For such product maintenance during the support stage, additional hardware implementations are not available and the number of hardware engineers is limited. However, if a software algorithm varies the load on the electrical parts, such as on the processor, the software updates incur thermal risk to the electronic products. Because the above-mentioned software changes occur frequently, verification of consumer electronic products must be efficient to address the large number of applications in use.

Thermal design is the realization of appropriate design specifications to satisfy thermal quality during utilization. Considering the complexity in thermal design throughout the product lifecycle, it is necessary to design the product architecture in thermal design view as early in the product development stage as possible. Otherwise, fatal iterative work will occur in the development stage or product quality will be degraded in the production or support stage.

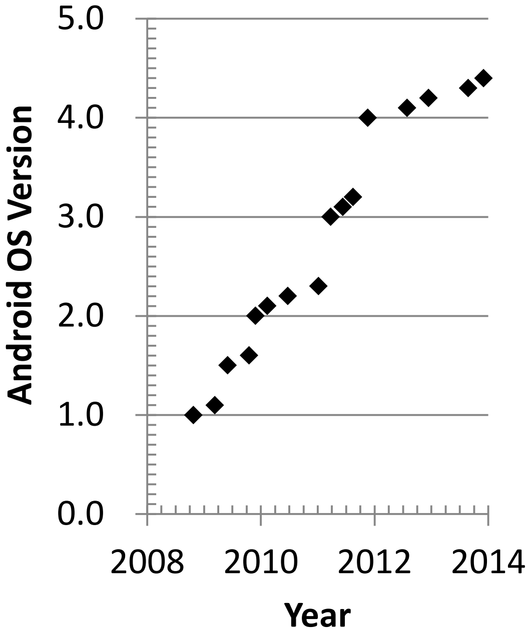


Figure 1.9 Example of software update release timings

1.1.3 Conventional thermal management

Various thermal management techniques have been developed for preventing damage and burns, such as those described in Figure 1.6. However, many of these techniques were developed for mechanical disciplines, while electrical and software approaches are being investigated and implemented nowadays.

Table 1.4 presents an overview of thermal management techniques for portable electronic products. The physical layout of modules, i.e., the electrical parts and mechanical structures, is an important consideration for heat spreading (Gurrum et al.

2012). In general, several heat sources are located inside a portable electronic product. Component layouts must maintain distances between these heat sources and promote heat spreading. In addition, heat transfer to components that are formed of high-thermal-conductivity materials is important for spreading heat. Metal frames, PWBs, and batteries are examples of components that exhibit high thermal conductivity. Thermal conductivity is a material property that refers to the amount of heat transferred per unit volume. In general, a metal, such as copper or aluminum, has higher thermal conductivity than plastic, glass, and air. PWB contains copper circuit patterns. Batteries such as lithium-ion batteries comprise high-thermal-conductivity materials as electrodes.

While designing component layouts to promote heat transfer and spread is a fundamental technique of thermal design, component layouts are also designed to perform various system functions. Therefore, component layouts must be designed with adequate investigations to consider the various constraints, not only thermal quality. To investigate a large number of cases, thermal simulations using computational fluid dynamics (CFD) for verifying the physical properties of prototypes (Seki 2008, Gurrum 2012) are often used to save time and costs. In CFD simulations, dimensions, layouts, and material properties of components, such as electrical parts and mechanical structures, are modeled; then, the heat dissipation value for each power consumption level of the many components is applied to heat sources such as semiconductors.

Because CFD simulation is performed with detail design information, thermal network analysis is also used with rough design information in the concept stage or beginning of the development stage. Because calculation is simple and not necessary to introduce special environment for simulation, thermal network analysis is often appropriate to system verification before design information is being detailed. Thermal network analysis is a common approach for estimating temperature rise in simplified systems (Hatakeyama et al. 2010, Yazawa and Bar-Cohen, 2002). In the calculation, thermal resistance of each object is expressed in equivalent thermal network. In this method, heat transmission is modelled as an electrical network, in which thermal resistance, temperature and heat transfer are analogous to electrical resistance, voltage and current, respectively.

Table 1.4 Thermal management techniques for portable electronic products

Thermal solution	Example
Hardware component layout	Separating heat sources Heat transfer to metal structure Heat transfer to battery
Heat spreading device installation	Cupper sheet / frame Aluminum sheet / frame Graphite sheet Heat pipe / Heat spreader
Thermal interface material installation	Thermally conductive sheet Thermal grease Thermal compound Thermal adhesive
Forced air convection device installation	Air cooling fan
Power reduction in electrical parts	Low-voltage processor Clock gating Power gating High efficiency power amplifier / power supply / display
Dynamic power management	Dynamic voltage and frequency scaling Thermal throttling

In addition to optimizing the layouts of components that perform basic functions in an electronic product for heat transfer, mechanical heat spreading devices are also often installed; they have the sole purpose of enhancing the thermal design. Besides additional copper and aluminum plates, graphite sheets made of carbon are typically used to spread heat near the product surface (Smalc et al. 2005). To transfer heat to a product's large surface area, a heat pipe utilizes the phase transition of water contained in a copper enclosure. Heat pipes that are now commonly used in laptops have been developed to be downsized to suit various products, including smartphones (Aoki et al. 2011, NEC 2013).

The installation of a thermal interface material (TIM) is another conventional thermal solution. TIMs have been developed and introduced into electronic products to transfer heat—especially between semiconductors and heat transfer or spreading devices. Most TIMs installed in electronic products have silicon or acrylic base and fillers that have high thermal conductivity. There are various TIMs with differing hardness values, installation methods, and thermal conductivities (Bayba and Washington 2012, Gwinn and Webb 2002). Thermally conductive sheet, which are often referred to as thermal pads or thermal cushions, are essentially soft sheets. Meanwhile, thermal grease is a high-viscosity liquid. Other forms of TIMs include moisture-cured liquids or adhesive tapes.

An air cooling fan is installed in many laptops and in some camcorders. However, this installation requires room for a fan and a channel for the air to flow; studies on small cooling fans are on-going. Instead of rotational fans, linear-stroke piezoelectric fans have also been studied owing to their compactness inside consumer electronic products (Kimber el al. 2009).

Power reduction in electrical parts is also a fundamental approach of thermal design. Installation of semiconductor processors that can be operated at lower voltages is effective at reducing power consumption (Tiwari et al. 1998). To suppress power consumption, deactivation of part of a large-scale integration process that is not necessary for completing an active processing task, such as clock gating or power gating, is implemented in many semiconductor processors. Technologies to reduce leakage current have also been developed, such as Fin field effect transistors (Hisamoto et al. 2000). Additionally, improving the efficiency of other electrical parts such as displays or amplifiers is necessary to develop more efficient portable electronic products.

Software power control techniques ensure a product's thermal safety, quality, and reliability (Jung 2012). Dynamic voltage and frequency scaling is a technique that controls the operating voltage and frequency of a semiconductor processor considering the processor's temperature and power consumption efficiency over short periods. Conversely, thermal throttling is a technique that suppressed the temperature rise, especially on the product surface. This technique controls the operating frequency of a processor and other states of peripherals, such as battery charging and display brightness, over relatively long sampling periods.

Besides various thermal management techniques for each module design, collaborative design is necessary from the viewpoint of the whole product. Thermal design of portable electronic products has become more complicated owing to various issues such as frequent software changes and variability in the components' characteristics. If product behavior is changed by software design, the thermal quality of the product is affected. Therefore, not only hardware but also software techniques are required to manage product temperature. However, simply implementing these thermal management techniques is not sufficient; verification for products across various disciplines is necessary for efficient product development. Otherwise, design changes may degrade the thermal quality or a developed product many contain unnecessary margins that hamper product quality.

1.1.4 Design approach to manage structural complexity of a product

To efficiently design complex systems, the relations between system elements must first be clarified. DSM was used to visualize the dependencies of elements of a product. Clarkson, Simons, and Eckert (2004) described a method for predicting the risk of design changes using a DSM. Change propagation paths were developed and reduced in terms of the likelihood and impact of each given change. Hamraz et al. (2013) developed an engineering change management method for assessing and improving the existing method via a requirement-based benchmarking approach.

Further, a domain mapping matrix (DMM) can be used to examine the interactions across domains. Using a DMM, Danilovic and Browning (2007) illustrated the interactions in a product development project that contained a minimum of five domains, including the product system, process, organization, tool, and goal. The product system consisted of product functions and design parameters, while the goal included requirements and constraints. To manage structural and behavioral complexity, Diepold et al. (2010) proposed combining structural and hybrid dynamical system models. The approach, which combined structural and mathematical modeling, resulted in a discrete-time dynamical representation of the system's dynamics. In this dissertation, the author applies MDM, which comprises both DSMs and DMMs, to describe the relations among the various system elements.

As an application of a matrix-based model, Michelena and Papalambros (1995) studied hierarchical optimization for product design. To optimize relations among decomposed elements of a system, the dependencies of design variables were described using a function dependence table. They applied this optimization method to design problems in the mechanical design of a power train. This approach can be applied to optimize the design parameters after the system architecture has been defined. In this dissertation, the author aims to specify the design parameters based on a system model that was developed for architecture design in thermal design view.

Because the thermal design targets all of the modules that include software, electrical parts, and mechanical structures, quality of developed products must be verified as a system. In other words, thermal design of the consumer electronic product are based on collaboration among design in multi-disciplines that include the electrical design to consume power consumption and mechanical design to spread heat, and software design to conduct semiconductor's behavior. While development of the electronic products is highly complicated, completion in concept design contributes to decrease unintended iterations of design and improve yield ratio in the production. Therefore it is very important to perform verifications in the early stage of the product development, especially in case that a system includes interdependencies among modules. In case that thermal problem is found at verification in the late stage of the development, iterative work will be fatal to maintain the development schedule. However thermal management techniques that described at previous subsection are important, balancing in module designs is also necessary. Otherwise, design changes including software changes may cause degradation of thermal quality or developed product contains much unnecessary margins against proper product quality.

For a collaborative design to prevent thermal problems such as low-temperature burn injuries, this dissertation proposes a design approach using a system model to derive product design specifications. This approach is also called a model-driven development method. Using a system model, the system design can satisfy the system requirements by allocating the requirements to the system components (Friedenthal et al. 2014). A system model covers the interactions between the product modules, which include all software and hardware components. To achieve a sufficient thermal quality, a thermal simulation model was developed based on a system model that describes the thermal behavior according to the product's basic functions.

To efficiently explore the design parameters of the modules, the author describes a system model by SysML. SysML can clarify the dependencies among the system elements, enabling model descriptions from operational, functional, and physical viewpoints (Balmelli 2007). This approach uses multiple viewpoints to separately address different engineering concerns while maintaining an integrated representation of the underlying design. Eguchi et al. (2012) proposed multilayer modeling of the structure, behavior, or requirements using SysML to describe the product design information. They utilized the method to carry out an impact analysis of changes to the initial design.

Thus, most research findings into managing structural complexity were applied during the product development or concept design. Thermal design of a portable electronic product is important throughout the stages of a product lifecycle, as mentioned above. Therefore, this dissertation applies thermal design using system modeling into product lifecycle stages, including development, production, and support.

1.2 Research purpose and scope

1.2.1 Research purpose

This dissertation aims to prevent low-temperature burn injuries during utilization of portable electronic products. The author proposes a thermal design method to achieve sufficient thermal quality and to prevent fatal iterative work in the various product lifecycle stages. In the proposed thermal design method, the author employs system modeling to describe the product architecture in thermal design view. An architectural description includes one or more architecture views (ISO 2011). To describe architecture using design parameters in the specified view, the relationship of the various design parameters among different views must be clarified. In accordance with the complexity of product design that involves different technological disciplines and various thermal problems in the product lifecycle, a system model is used to describe the behaviors of heat generation and transfer as well as the interactions of the system elements. The proposed method should be practically applicable product development. The aims of this research are summarized below:

- To derive thermal design specification for portable electronic products of satisfactory thermal quality in which the possibility of low-temperature burn injuries is predicted using software and hardware design parameters.
- To prevent fatal iterative work, factors that affect product thermal quality are continuously managed among all concerned parties, including module design groups, during the module development stage.
- To manage thermal problems efficiently in the development, production, and support stages, a system model is reused that reflects the changes in the heat generation condition.

1.2.2 Research scope

Characteristics of a portable electronic product in thermal design view

According to the above-mentioned research purpose, the author defined the research target as developing the proposed design method. In this dissertation, the surface temperature of a portable product was decreased below conditions that could possibly cause low-temperature burn injuries. The portable electronic products were typical small consumer electronic products, such as smartphones, tablets, digital cameras, and video game players.

This dissertation covers changes in heat generation conditions according to the operating condition of a semiconductor based on software commands. The software in this dissertation is the OS that controls the product's electrical parts including the semiconductor processor. The design parameters of the software include states of electrical parts, such as the operating frequency of a semiconductor processor, the state of battery charging, and the states of the peripherals.

To describe a prolonged utilization of the product, certain states of each electrical part were considered to be used for individual purposes, such as playing movies or games. The surface temperature of the product was considered to be its steady-state temperature. The temperature rise time was considerably shorter than the required usage time, and was hence, ignored.

As described in Table 1.1, electronic products including portable electronic products have very short development periods in comparison with products in other categories such as automotive and professional electronics. Then, the products are developed in sequence. Therefore, many portable electronic products were developed referring to parent design information or similar products. Although details of the design information are uncertain, some basic functions and principal components of the products are often expected experientially at the time of the architecture design.

The composition of system elements is simplified as much as possible to describe system behaviors across different technological disciplines. When a thermal simulation based on the system model is performed in the concept or the early stage of development, detailed design information is limited; it may also not be possible to rigorously estimate the product's quality. Even if the simulation accuracy based on the simple structure of the system model is rough, it is often practical to consider this information with regards to design margins to minimize the possible degradation of thermal quality.

Proposed thermal design approach

The thermal design approach proposed in this dissertation is based on system analysis and a definition process for architecture design. INCOSE (2015) described that the purpose of system analysis is to provide a rigorous data and information foundation for technical understanding to aid decision-making across the product lifecycle. The activities of system analysis include preparation, performance, and management. System analysis is performed to select architecture alternatives that frame stakeholder concerns and meet system requirements.

Figure 1.10 shows the proposed thermal design approach for a portable electronic product using system modeling. For the architectural design in thermal design view, the system model was developed to describe heat generation and transfer behaviors. Equations based on the thermal behaviors are also described using design parameters that refer to both hardware and software components controlling the electrical parts. To predict thermal quality, the thermal simulation based on the system model is referred to the condition of low-temperature injuries.

To prevent fatal iterative work, target value boundary conditions for the module designs were determined to manage the factors that affect the thermal quality; these could then be shared with concerned parties including the module design groups. The target values are referred to as initial target values (ITVs) (Seki et al. 2011a). To describe the relation of the system elements in thermal deign view, a multiple-domain matrix (MDM) was employed in this dissertation. An MDM utilizes DSMs. Using an MDM, the boundary conditions of modules including ITVs were clarified.

For thermal management methods to eliminate low-temperature injuries during utilization, thermal design specification in the development and support stages was derived using the system model to describe the architecture in thermal design view. To manage the variability in component characteristics in the production stage, the system model was reused to describe the interactions between heat generation and transfer.

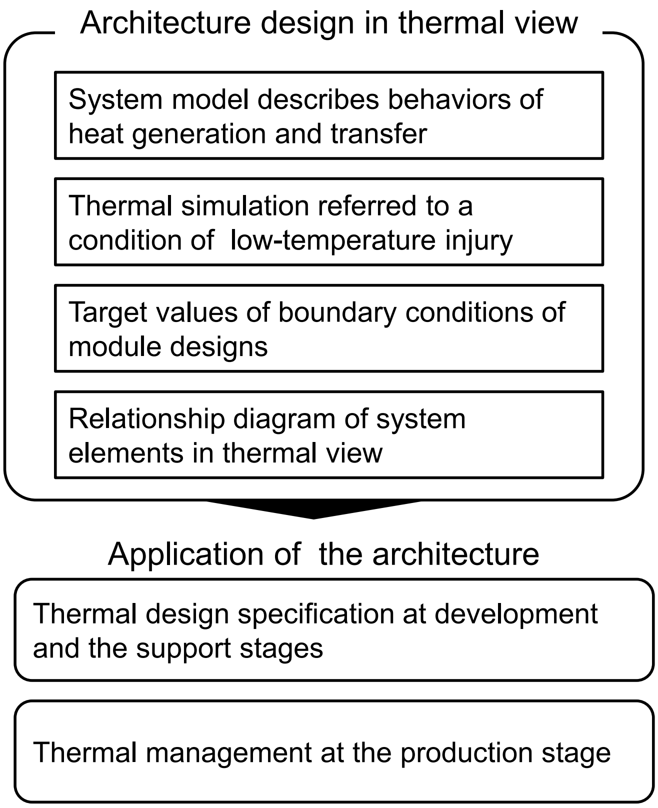


Figure 1.10 Proposed thermal design approach

Novelty of the proposed research

This dissertation proposes a collaborative design approach in a distributed design environment. For the distributed design sites of consumer electronic products, Seki et al. (2012) investigated a module-based design approach using SysML. They proposed structural and functional modeling that enabled all the design sites to share design information with the product model. They proposed the use of ITVs as tentative boundary conditions among modules such as electrical parts and mechanical structures (Seki et al. 2011a). Seki and Nishimura (2011b) also proposed a thermal design framework for a distribution design using DSMs and DMMs to analyze the physical interaction of modules. As shown in Figure 1.11, they determined the thermal interfaces of modules in a non-portable consumer electronic product that had an air cooling fan. In their study, forced air flow to dissipate heat was assigned as an ITV.

In these studies, although ITVs were practically used to communicate with each module design, these studies were based on the thermal design of hardware modules; the states of the electronic parts were not included in the design parameters. Because many functions of a portable electronic product are realized by software, the system model in this dissertation includes both hardware and software modules to evaluate heat generation during utilization. It is expected that thermal problems during the utilization of new applications such as video games (Consumer Reports 2012) can be simulated with design parameters including the states of the electrical parts. The description of a product's thermal behavior enables us to simulate its thermal quality even after product development. The author applied the system model to simulate how a product's thermal quality was influenced by software updates in the support stage and assess the variability in component characteristics in the production stage.

In addition, refereeing to a thermal simulation with the conditions under which low-temperature burn injuries occur enables the simulation of a product's thermal quality with the module's design parameters. To prevent accidents using the portable electronic products such as a smartphone, a laptop PC or a video camcorder (National consumer affairs center of Japan 2014, National Institute of Technology and Evaluation 2015, Canon 2012), this dissertation estimate possibility of low-temperature burn injury using thermal simulations. To manage factors that affect the thermal quality, this dissertation visualizes system elements and their interactions using the above-mentioned MDM. Concerned parties in referring thermal simulation including both hardware and software design groups can collaboratively perform thermal design considering utilization of the product.

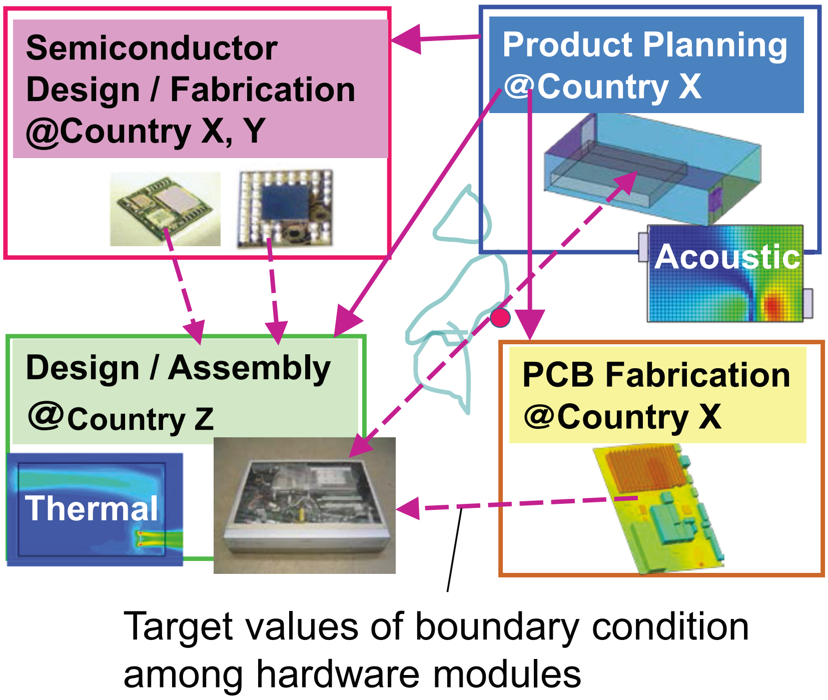


Figure 1.11 Thermal interfaces between hardware modules for distributed design (Seki et al. 2011a)

1.3 Structure of the dissertation

This dissertation describes the thermal design of a portable electronic product with the aim of achieving satisfactory thermal quality and preventing fatal iterative work through the product lifecycle. This dissertation consists of five chapters. Chapter 1 describes the background and purpose of this research. Chapter 2 covers architecture design in thermal design view. The architecture design considered the distributed design environment of modules. In this chapter, the system model describes heat generation and transfer behaviors. Target values for the module design to prevent fatal iterative work are also defined in this chapter. Chapter 3 describes the thermal design specifications of a portable electronic product. Thermal simulations based on the system model were performed to prevent the conditions under which low-temperature burn injuries occur. The thermal design specifications in the development stage and thermal management in the support stage are also described in this chapter. Chapter 4 introduces an application to a production system that takes into account the variability in the component characteristics. The system model was developed to describe the temperature dependency of the leakage current effect of a semiconductor processor. Finally, Chapter 5 provides conclusions and future work.

Related to the author’s academic publications, Chapter 2 is based on a paper presented at an academic conference (Seki at el. 2015). The simulation model and application in the support stage in Chapter 3 are based on a journal article concerning product lifecycle management (Muraoka at el. 2015). Two applications in the development stage in Chapter 3 are based on papers presented at two academic conferences (Muraoka at el. 2013a, Muraoka at el. 2013b). The content of Chapter 4 is based on a journal article on the topic of mechanical engineering (Muraoka at el. 2016).

Chapter 2

Architecture Design within a Distributed Design Environment in Thermal Design View

2.1 Introduction

In this chapter, the architecture design of a portable electronic product is described in thermal design view. First, the thermal behavior related to the basic function of the product is modeled. To describe the architecture in thermal design view, the Systems Modeling Language (SysML) is employed. A system model describes the heat generation and transfer. The author considers the distributed design environment of module design during product development. To analyze the system in thermal design view, equations based on the thermal behavior of the components are described using the design parameters of the modules.

The system model for the thermal design management is then described. The target values of the module design are defined to prevent fatal iterative work. The target values, named internal target values (ITVs), are the boundary conditions of the modules in thermal design view. The ITVs that satisfy the thermal quality requirements of the product are explored with module designs at the concept design stage or at an early development stage.

To describe the relationships between the modules in thermal design view, a multiple-domain matrix (MDM) is employed. MDM comprises design structure matrices (DSMs) for function, behavior, and structure. To define the architecture, architecture candidates are assessed in thermal design view. Illustrating the system elements using MDM clarifies how the ITVs are related to the behavior and structure of modules for each architecture candidate. The architecture definition in the thermal design view is performed to assess the candidates to determine if they satisfy the thermal quality requirements. The author also describes the proposed thermal design process using a system model.

2.2 Development of a system model in thermal design view

2.2.1 System modeling of a portable electronic product

An overview of the system modeling process using SysML in the thermal design view is shown in Figure 2.1. For the performance of a portable electronic product in a certain use case, first, the necessary functions are described. Figure 2.2, which is the same as the diagram on the upper left in Figure 2.1, shows the sequence diagram for functional design. This figure describes the simplified basic functions that are performed in sequence. In this case, the functions for movie recording with a digital camera or the camera feature of a smartphone are illustrated as an example. After the product is turned on, power is supplied to the electrical parts, and optical functions such as focusing light and image sensing are performed. During the use case, data processing is continued for a prolonged period.

When the function is performed, a semiconductor processor that manipulates data is activated to operate at a certain state. The diagram on the upper right in Figure 2.1 is same state machine diagram shown in Figure 2.3. The state transition is described in this diagram. A state is assigned for each function, and the state of a semiconductor processor, such as a CPU core within an application processor or a digital signal processor (DSP), is indicated by an operating frequency while performing a function. In this example, a processor is activated at the operating frequency of one of three states. Such a processor consumes power in proportion to the operating frequency. The power consumption can be estimated by identifying the state of the processor performing the data processing function.

During the operation, the product exhibits the thermal behaviors of heat generation and transfer. The diagram at the lower right in Figure 2.1 is the activity diagram. The thermal behavior described in this diagram is shown in Figure 2.4. Because the temperature rise depends on the product structures, the thermal behavior that creates a temperature rise is allocated to the structures as shown in the figure. In the first activity in Figure 2.4, the software that controls the electrical parts performs data processing. The software assigns the states of the electrical parts at that particular time. Then, the electrical parts generate and transfer heat while consuming power for data processing, all of which is dissipated as heat. The mechanical structures transfer heat from inside the product to the surface.

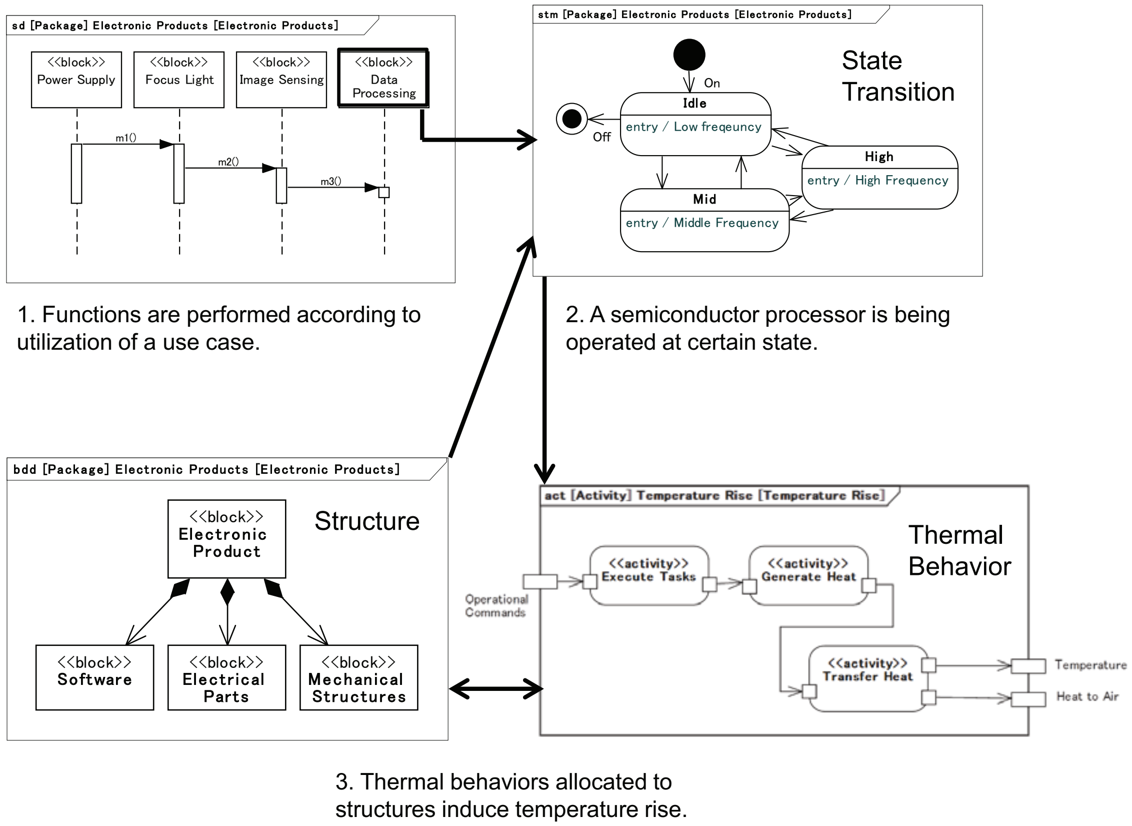


Figure 2.1 System modeling in thermal design view

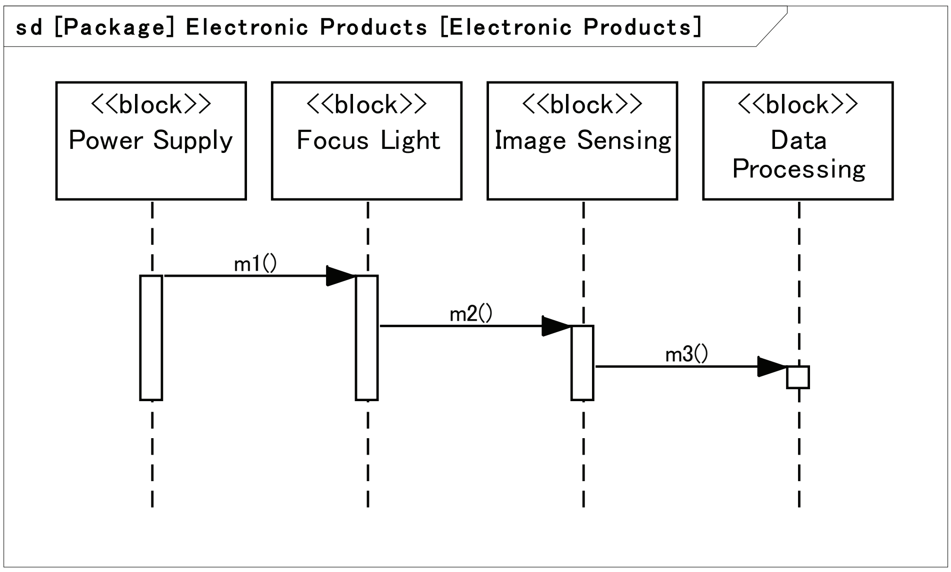


Figure 2.2 Sequence diagram for functional design

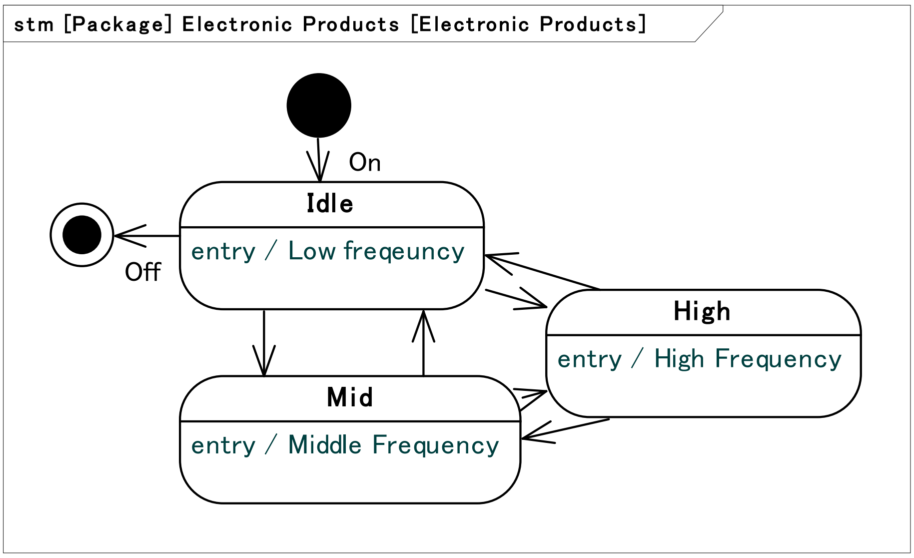


Figure 2.3 State machine diagram for processor power state

The structural elements of the system are described using the block definition diagram shown on the bottom left in Figure 2.1. The product structure consists of modules such as software, electrical parts including a semiconductor processor, and mechanical structures. In addition to the heat generation that occurs in the electrical parts, heat is also transferred from the electrical parts to the mechanical structures. Therefore, the activity of heat transfer is decomposed to allocate it to both the electrical parts and mechanical structures. The activity of heat generation is allocated to the electrical parts. Because the design of the electrical parts and mechanical structures are often performed in different organizations, the management responsibility for the related design parameters must be distributed consistent with the decomposition.

By analyzing the three behaviors shown in Figure 2.1, the architecture candidates are developed in the thermal design view. Power consumption and temperature rise are simulated with equations described later. To obtain architecture candidates that satisfy the thermal quality requirements, iterations of the modeling process are usually performed. If the surface temperature of the product is expected to exceed the target for thermal quality, the states of the electrical parts or the allocation of thermal behaviors can be reviewed. For example, heat generation caused by data processing occurs in a semiconductor processor. Either an application processor or a digital signal processor

(DSP) is used to perform the data processing function. The allocation can be modified to improve heat generation and transfer, as described in later description.

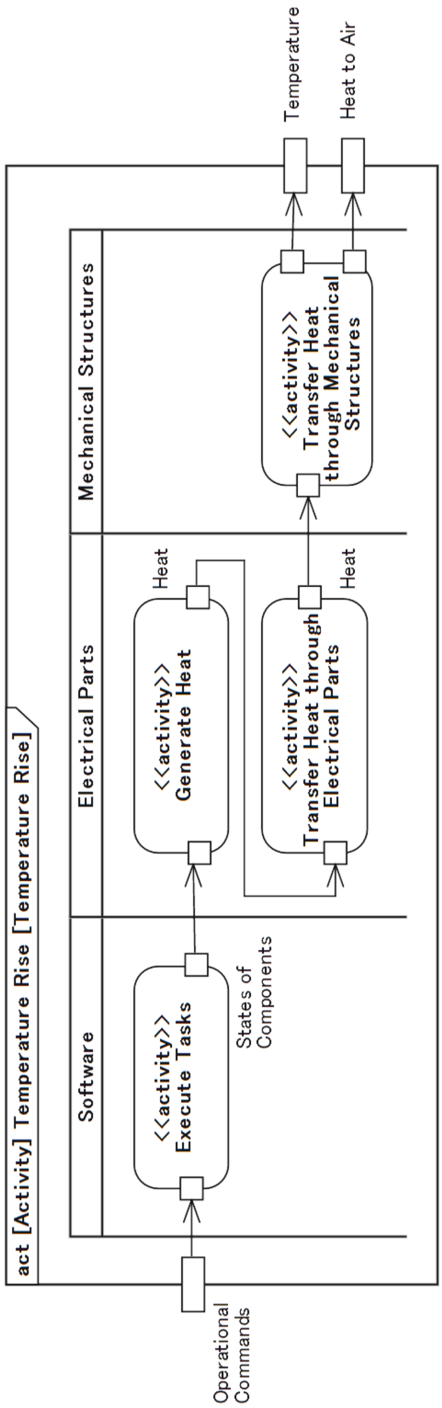


Figure 2.4 Activity diagram for temperature rise

2.2.2 Preparation for system analysis using module design parameters

To analyze the architecture candidates in thermal design view, this dissertation defines a thermal system that consists of elements related to temperature rise for the purpose of system analysis. The block definition diagram shown in Figure 2.5 shows that the thermal system has a reference association path with the structure of a portable electrical product consisting of three modules, specifically software, electrical parts, and mechanical structures. The activities of the thermal behaviors are allocated to the thermal system. As mentioned above, the activity of task execution is to assign states of the electrical parts to perform the basic functions. Other activities, such as heat generation and heat transfer, are associated with constraints that are determined by the equations for the activities. To allocate the activities to modules as shown in Figure 2.4, the heat transfer activity is decomposed into heat transfer through the electrical parts and heat transfer through the mechanical structures. As product development progresses and becomes more detailed, the thermal system can be further decomposed to indicate the behaviors to be analyzed.

The temperature rise is calculated using equations for heat generation and transfer. The parametric diagram in Figure 2.6 shows the relationships between the equations and design parameters to estimate temperatures for the states of the electrical parts, such as a semiconductor processor. By using these equations for heat generation and heat transfer, it is possible to explore design parameters that satisfy the product thermal quality requirements. For example, operating voltage and load capacitance are design parameters for a semiconductor processor. To perform the data processing function, a semiconductor processor consumes power when operating. The amount of power consumption depends on the operating frequency, voltage, and load capacitance when the processor is fully activated. Almost all of the power consumed is converted into heat and dissipated from the processor. In addition to the semiconductor processor, a power supply unit and peripherals also consume power. Because the power supply losses are also converted into heat, the efficiency of the power supply is also a design parameter for the electrical parts in the thermal design view. Peripheral devices such as the display, speaker, and camera also consume power and generate heat.

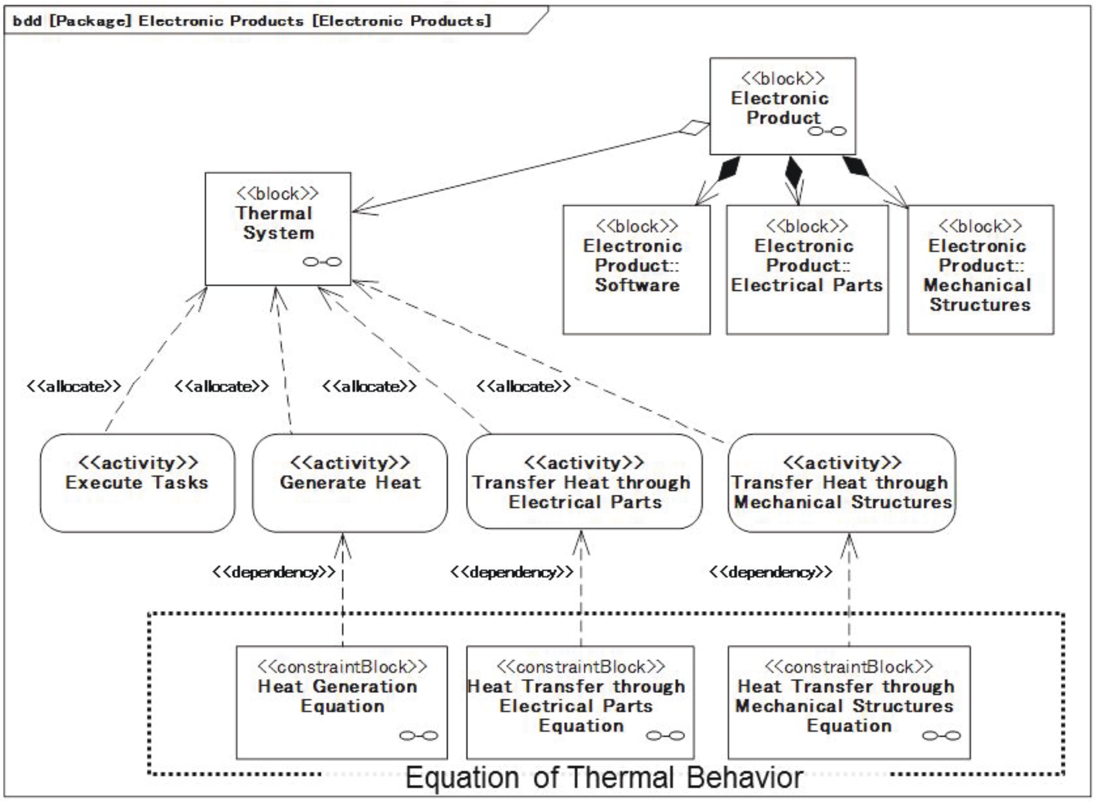


Figure 2.5 Composition of thermal system elements

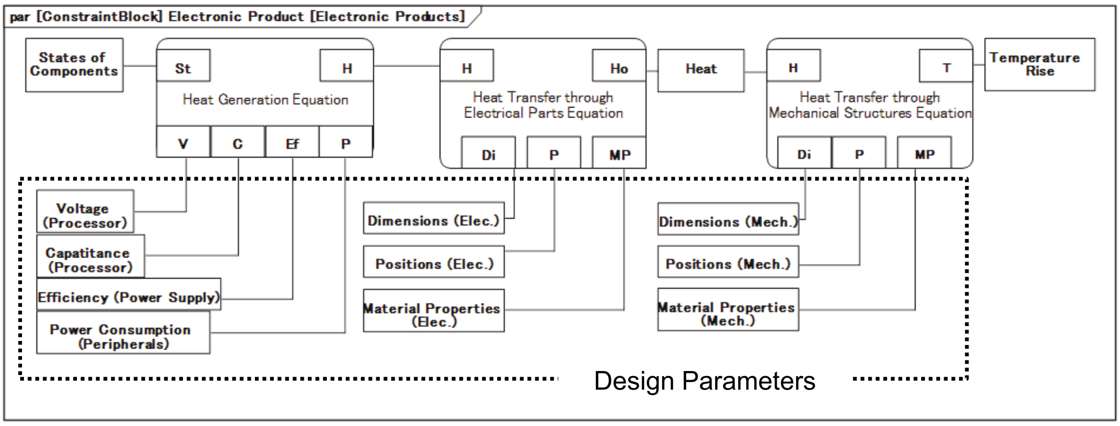


Figure 2.6 Relationships between equations and design parameters for predicting temperature

The design parameters related to heat transfer include the dimensions, position, and material properties such as thermal conductivity. Both the electrical parts and the mechanical structures transfer heat. The two heat transfer equations are for the electrical and mechanical modules and are most likely calculated by individuals. Because many electrical parts are designed by component suppliers and commonly used in many different applications, the dimensions and material properties of the electrical parts are already defined in the component specifications. If the difference between the design parameters for heat transfer of a custom-designed electrical component and that of an off-the-shelf component is negligible and can be ignored for the specific range of temperature rise, then the heat transfer through the electrical parts can be simplified in the equations. On the other hand, the mechanical structure can be flexibly designed to transfer heat in general.

Because a system model describes the behavior of components that are the responsibility of multiple disciplines, exploration of the design parameters can be performed in the presence of various technological design groups with various viewpoints. Even related disciplines can differ in their views. The interactions between design parameters that cause temperature increases are analyzed quantitatively to support the architecture assessment. Because enough information for modeling is not always available for the selection of an appropriate architecture candidate, a system analysis should be planned to consider the accuracy of simulation, the criteria for evaluation, and the detailed schedule of the product development. The accuracy of the simulation depends on the granularity of the decomposition and the degree of certainty of the design information. If at the concept or the early stage of development, the available design information details are limited or uncertain, it is practical to consider design margins.

2.3 Thermal design management using the system model

2.3.1 Setting target values of boundary conditions between modules

To prevent fatal iterative work, this dissertation proposes to define and manage the target values for module designs in the thermal design view. The author aims to set feasible targets at an early stage of the development instead of at the time of integration and verification of the product. The target values are the boundary conditions of the module design for managing thermal quality.

The boundary conditions between modules are shown in Figure 2.7. The upper diagram in Figure 2.7 is the internal block diagram that describes the interfaces between modules in the thermal design view. As described in the activity diagram shown in Figure 2.4, the software that controls the electrical parts assigns states to them consistent with the operational command for a particular use case. While electrical parts, such as the semiconductor processor, perform data processing, heat is generated and is transferred through the electrical parts. Then, the heat is transferred to the mechanical structures and dissipated to the air through these structures. Because heat transfer activity causes a temperature rise in both the electrical parts and mechanical structures, the surface temperature of the product increases. The boundary conditions between modules include the states of the electrical parts, heat, and temperature. This dissertation manages these three boundary conditions as target values of module design to satisfy the thermal quality requirements of the product.

The target values, such as states of components, heat, and temperature, are indicated in the diagram of Figure 2.7, which is the same parametric diagram shown in Figure 2.6. As mentioned above, these boundary conditions can be calculated by using the design parameters of the module designs. Therefore, exploring design parameters that satisfy the thermal quality requirements of the product enables setting target values for the boundary conditions. The boundary conditions, designated as ITVs, are distributed to the module designs. Because each module design can be independent, the modules are then developed to satisfy the ITVs. This operation influences the thermal quality of the product.

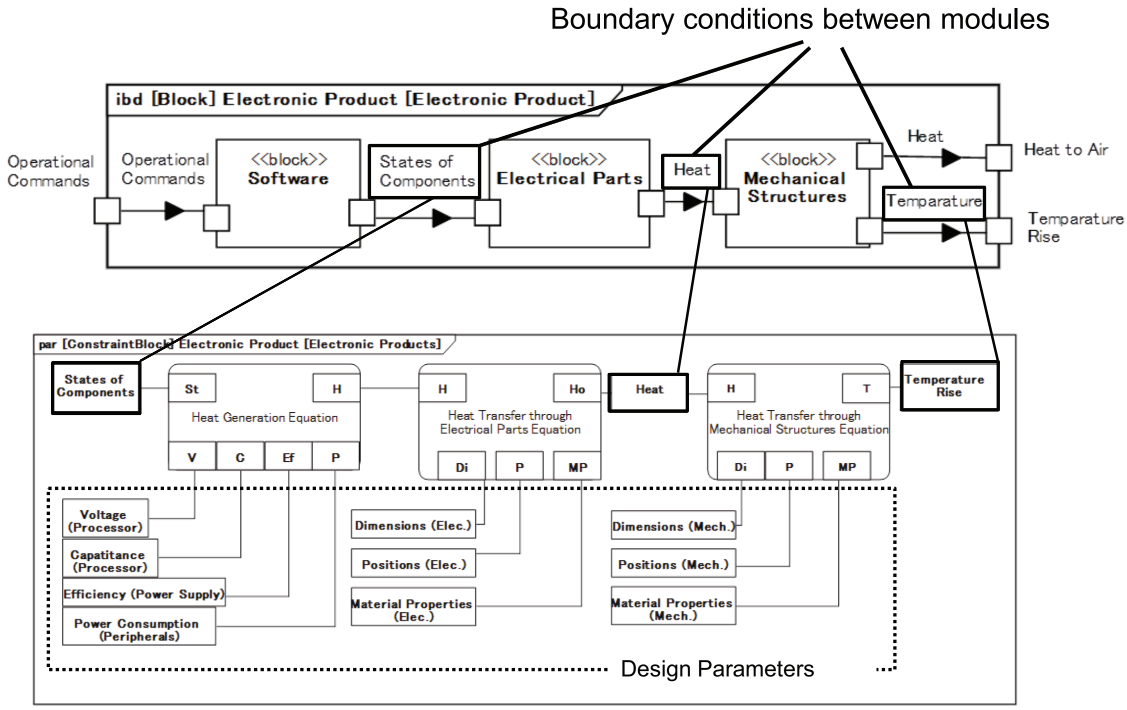


Figure 2.7 Boundary conditions between module designs

In general, the task of developing consumer electronic products, including portable electronic products, is divided among different organizations and often distributed to different enterprises. Therefore, the lack of communication between independent module designs must be compensated for to develop a product that both satisfies the thermal quality requirements and eliminates unproductive design iterations. Figure 2.8 illustrates how the ITVs are created. To meet the system requirements, a system engineer or an architect develops the system model at the concept stage by designing the system architecture; this is done together with the concerned parties including the principal members of module designs and product planning. The system requirements are defined in the technical view, and they specify the system characteristics, attributes, functions, and performance that will meet the stakeholder requirements (INCOSE 2015). In this dissertation, the thermal quality requirements during utilization and the dimensions for providing appropriate portability are also included in the system requirements for a portable electronic product.

In exploring a module design that satisfies the thermal quality requirements of the product, the thermal design is performed using a thermal simulation based on the system model. Combinations of design parameters are analyzed using equations that describe thermal behavior. Because the thermal behavior is simply simulated using the design parameters of the modules, the module design can be explored by the concerned parties at a meeting. Otherwise, the analyses related to each module are performed by the relevant design group using that group's choice of simulation method. If the design information for the parent product is available, the exploration can be started on based on prior experience. Experimentation using prototyping or similar products also helps to explore suitable design parameters. The design parameters must be acceptable to each module design group. For example, the software design group defines how basic functions are performed by taking into account which electrical parts can be used. The mechanical design group defines where the hardware components, including the electrical parts, are located. The electrical design group defines the types of major electrical parts that are mounted to satisfy requirements in the various views including thermal design, taking other module designs into account. Because the design parameters selected must undergo the product development process, exploration of the design parameters is expected to be iterative.

After the combination of design parameters that satisfy the system requirements, including the product thermal quality requirements, are defined, the boundary conditions between modules are distributed to the module designs as the ITVs. Because the module design groups are often located in different countries or different enterprises, the lack of communication between groups about module designs may cause unproductive iterations with design changes. For a design change caused by a requirement change or compensation for inconsistency in module design, the ITVs are iteratively updated consistent with additional design exploration of modules using thermal simulation based on the system model as necessary. When the module developments satisfy the updated ITVs, this results in satisfaction of the criteria for the product thermal quality.

To prevent fatal iterative work and to facilitate adapting to design changes, ITV parameters should be chosen that positively affect the thermal quality requirements and allow control of the values during product development. At the early stage of development, many design parameters are abstract or uncertain until the details of the design information are defined. When the thermal system is decomposed, the number of parameters, such as boundary conditions between modules, is increased. It is important to determine how much detail is present when the thermal system is decomposed and therefore to select ITV parameters consistent with the goals.

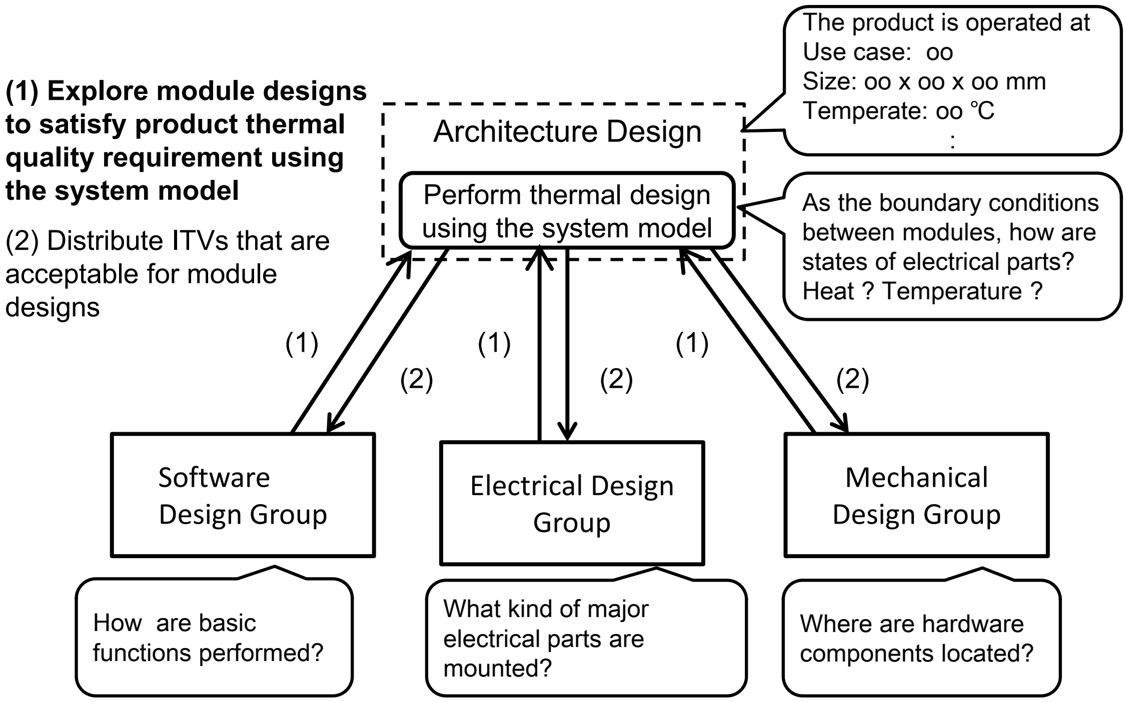


Figure 2.8 Communication for architecture design between distributed module designs using ITVs

2.3.2 Describing the relationships between the modules using MDM

To promote communication between module design groups, this dissertation describes the relationships between the components of the modules in thermal design view. As architecture design progresses, structural elements in the system model are tentatively defined. As an example, Figure 2.9 shows the component layout of a digital camera. The components are the principal and typical ones of portable electronic products. If the design information of a parent or a similar product is available, some of the principal components can be defined at the concept design stage. The application processor and DSP for data processing are mounted on a printed wiring board (PWB). A lens unit for image sensing is one of the principal components of a digital camera, and the structure is quite similar to that of a smartphone. There are nine components shown in the figure. Other electrical parts, such as a power supply unit and memory, are also mounted on the PWB. The image sensor for a camera function is also attached to the lens unit.

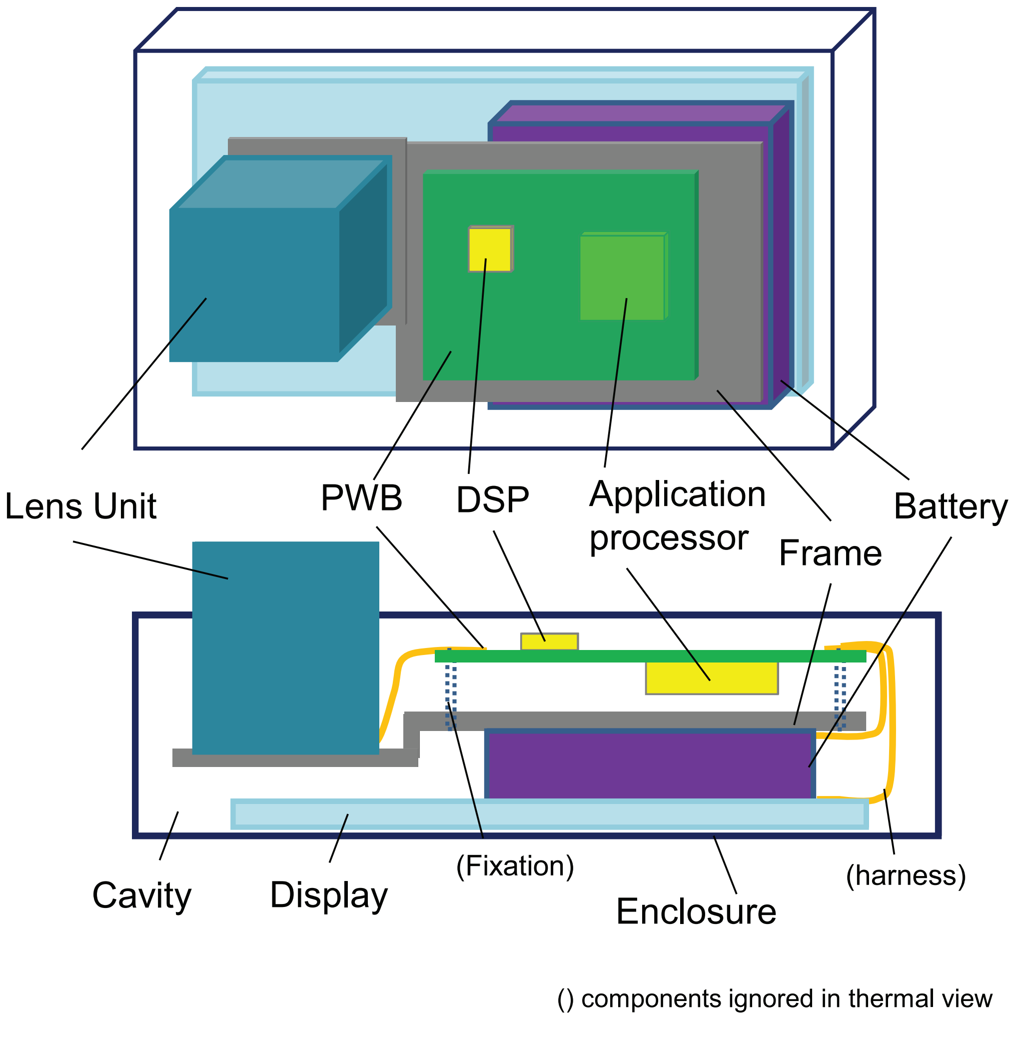


Figure 2.9 Example of a component layout of a digital camera

Figure 2.10 shows an MDM that comprises DSMs and domain mapping matrices (DMMs) to describe the relationships between the system elements of the digital camera. The rows and columns of MDMs correspond to the composition of the system model, which includes functions, behavior, and structures. The function DSM constitutes the correlation matrix between the functions from the sequence diagram. The function–structure DMM is filled with functional allocations to the various structures. For example, a data processing function is allocated to a DSP, which is categorized as an electrical part.

The activity of thermal behavior and the boundary conditions between the first two activities in the software and electrical parts are allocated as behaviors. The boundary conditions are the states of the components that are allocated to the electrical parts. As a result of task execution, six electrical parts become active, consuming power and generating heat. The power consumption depends on the states of the semiconductor components to which the function is allocated.

Other boundary conditions such as heat are described in the DSM of the structures on the bottom right in Figure 2.10. There are three modules, such as software, electrical parts, and mechanical structures. The software includes an OS and an application and is also included in the structural elements of the product. While the OS controls the electrical parts, the operational commands depend on the application. The behavior that connects the hardware components is heat transfer. Heat is transferred from the electrical parts to the mechanical structures, which include a cavity. In the MDM in Figure 2.10, twelve paths of heat transfer between the modules are present. The heat generated by the electrical parts is transferred both to PWB and to a cavity that is filled with air. After the heat from PWB is transferred to the frame, then it is transferred from the frame to the enclosure. Finally, the heat is dissipated in the air.

Because the binary expression of heat transfer relationships between components does not indicate how much heat is transferred, the author describes the heat transfer value in the cells in the portion of the structure DSM of the hardware components. This portion of the matrix is on the bottom right of the MDM in Figure 2.10 and is named the thermal coupling matrix (TCM). Figure 2.11 shows the part of TCM for the case where the data processing function is allocated to DSP. In TCM, the values for heat transfer between structural components are shown in the cells with a clear background. Because heat transfer has direction, there are two types of values in the matrix. Negative value above the diagonal means that heat is transferred from a component in row to a component in column. On the other hand, positive value above the diagonal means that heat is transferred from a component in column to a component in row. Values below the diagonal express the same heat transfer relations as above using the reversed sign. Also, temperatures of components are shown in diagonal cells. The temperatures of components are shown in the diagonal cells on a blue background.

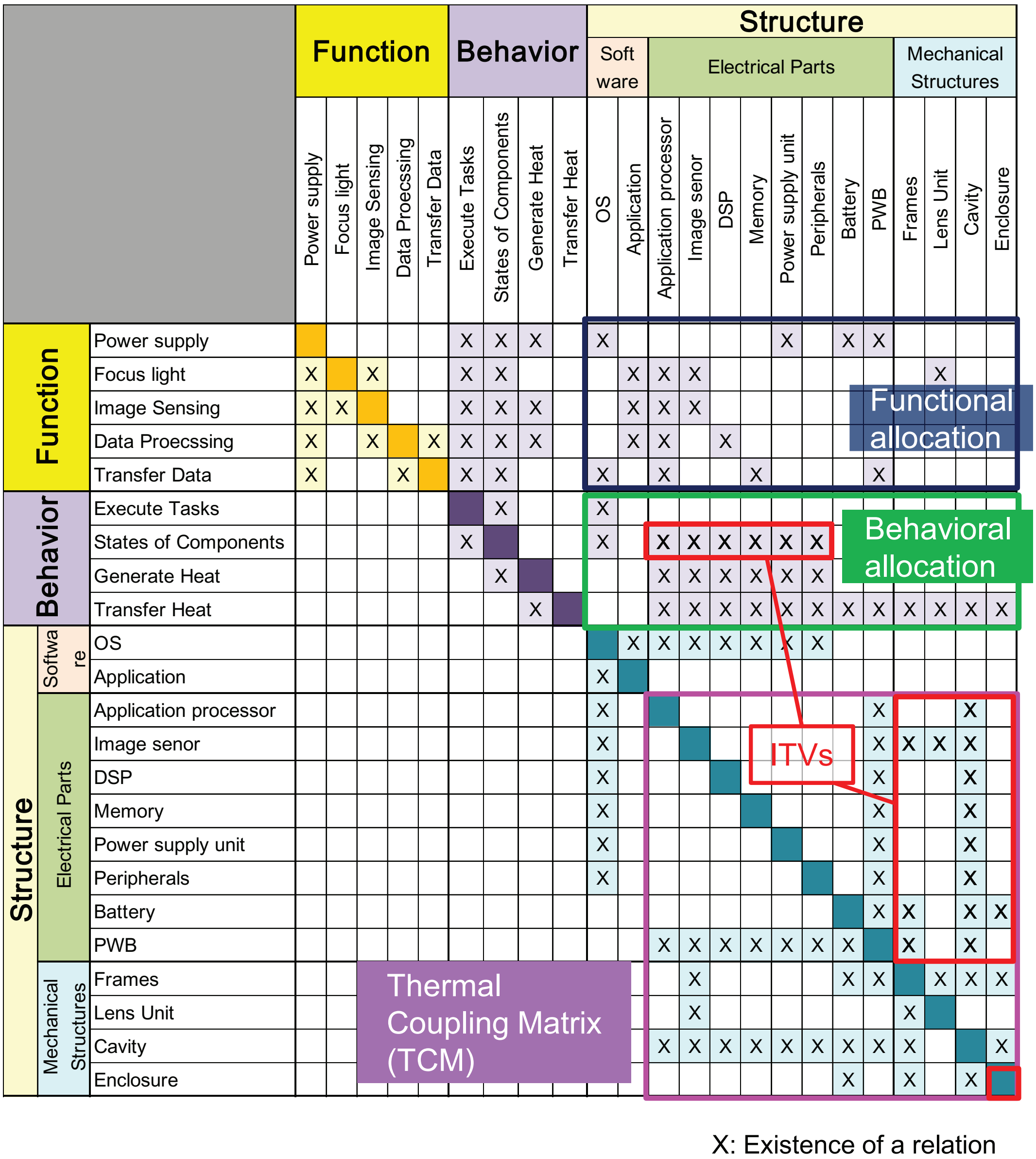


Figure 2.10 Relationships of system elements described in MDM

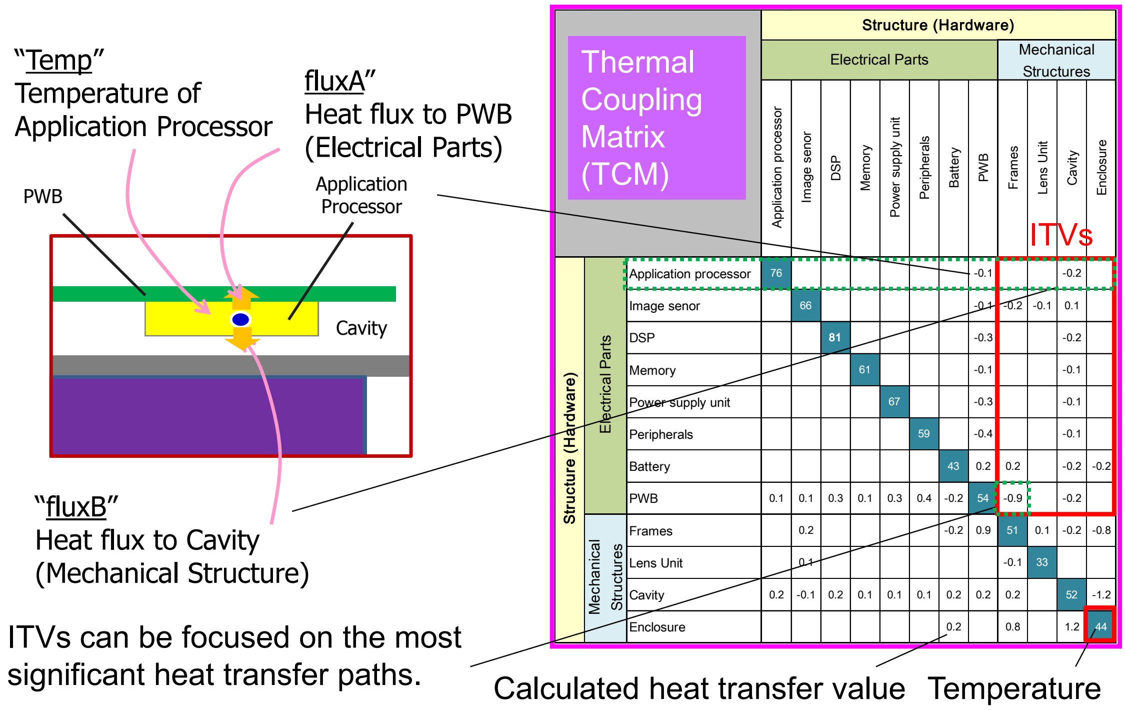


Figure 2.11 Thermal coupling matrix（TCM）

The elements of TCM can be quantitatively described using a thermal simulation. For example, the heat generated at the application processor is transferred to both the cavity and PWB. In TCM, it can be seen that more amount of heat from the application processor is transferred to the cavity of the mechanical structures than to PWB. Then, the heat is transferred to the enclosure via various paths. The surface temperature of the product depends on the heat dissipation from the enclosure. The calculated temperatures are given in the diagonal cells of TCM. The author applied a CFD simulation to calculate the values of heat transfer and peak temperatures of the components in this subsection. Instead, of a CFD simulation, a simplified simulation using a thermal network analysis can be used; the thermal network analysis is applied in Chapter 3. For both CFD and thermal network analysis, information of each component including dimensions, position and material properties such as thermal conductivity are necessary. A thermal network analysis based on simple equations is often practical, especially at the concept and early stages of development. Because the details of the component geometry are difficult to express in network analysis, the calculated temperatures are the averaged temperatures of each component. To calculate the temperature distribution in a component, the component geometry is divided. Otherwise, for the evaluation, it is practical to add some margin to the temperature distribution to compensate for simulation uncertainties.

Because module design is detailed, and it changes often to achieve compromises with various requirements during product development, the selection of ITVs is important. Updating ITVs during development is expected. It is desirable that ITVs positively affect thermal quality requirements and have few constraints in adapting to the changes in the module design. If a change in the module design satisfies ITVs without changing the target value, a design change in other modules can be avoided. However, if the change in ITVs causes a limited change in the module design, the affordable selection of ITVs might be acceptable for module designs. Therefore, it is important to clarify how the components interact with each other and what constraints or concerns are associated with each component. While major electrical parts such as a semiconductor processor are difficult to replace with an alternative, some off-the-shelf parts are relatively easy to replace. An enclosure in a mechanical structure has more constraints in terms of dimensions and appearance than a frame does. Implementation of a sheet or adhesive often has fewer constraints if the production process can handle the implementation.

For efficient thermal design management, it is practical to eliminate ITVs that do not significantly affect thermal quality. Number of heat transfer paths is increased with number of components. If the physical structure is simple and certain heat transfer paths are dominant, it is practical to focus on the dominant heat transfer paths or regard sum of transferred heat as ITVs. Reducing the number of ITVs contributes to reduced management costs and increased flexibility for changes in module design. As shown in Figure 2.10, there are 12 heat-transfer paths designated as ITVs between electrical parts and mechanical structures. Power consumption of the electrical components is 2.2 W in total. If the paths that transfer less than 5% of the total heat are ignored, the number of ITVs can be reduced to seven. The number of components is expected to increase as module design becomes increasingly detailed through the course of development. Prioritizing ITVs contributes to improved efficiency of product development.

The visualized relationships between the system elements in the thermal design view promote understanding of the influences on module designs. If changes in a module design cause inconsistency in satisfying the ITVs mentioned above, the thermal quality of the product will be degraded. By illustrating ITVs in MDM as boundary conditions between modules, the influence of design changes can be traced, and ITVs that are related to the design change can be identified. Although diagrams using SysML can describe such interactions between system elements, MDM simply expresses the relationships with one matrix. The common understanding helps to facilitate design changes without unnecessary additional iterative work.

2.3.3 Architecture definition in thermal design view

In this subsection, the developed architecture candidates are assessed and defined in thermal design view. For this assessment, the author uses the thermal simulation based on the system model and MDM including TCM. Throughout the definition process, the features, properties, and characteristics satisfying the problem are assigned to the architecture so it can be implemented using available technology (INCOSE 2015). Therefore, the practical architecture candidates for the final design should be designated using the definition process.

In the thermal design of a portable electronic product such as a digital camera, both the component and surface temperatures are not allowed to exceed the values set as criteria for product thermal quality. The structural layout of the portable electronic product shown in Figure 2.9 is discussed in the thermal design view. Components such as semiconductor processors have a stipulated temperature range during operation. Operating those electrical parts at a temperature that exceeds this range may cause damage to the components or malfunctions. A product surface that forms the skin of an enclosure presents another kind of risk during utilization of a product. A surface temperature equal to or greater than 44 °C may cause low-temperature burn injuries when a user has prolonged contact with the product. Otherwise, the hot surface of the product may cause user discomfort. By using a thermal simulation based on the equations described in Figure 2.6, it is possible to assess if both the temperature target and design parameters of the architecture candidates are appropriate for satisfying the product thermal quality requirements.

To prevent thermal problems, the portable electronic product must be designed to suppress peak temperatures at those critical points. Figure 2.12 shows the component layout in a cross-sectional view. The structure of a portable electronic product has a temperature distribution. To reduce the peak temperatures, heat generated within the product should be spread through one or both mechanical structures and electrical parts. An enclosure surface with a uniform temperature is thermodynamically optimal. Reducing power usage is also an important principle of the thermal design because some of the power consumed by electric parts is dissipated as heat. In addition, electrical parts that generate large amounts of heat are best mounted with space between the components to distribute the heat on a PWB. Implementation of heat conduction away from the electrical parts is also a principle in the thermal design of electronic products.

In this subsection, MDM is used to assess the architecture candidates in the thermal view. The purpose is to ensure both user safety (limited enclosure temperature) and camera function (limited internal module temperature). As shown in Figure 2.13, the three architecture candidates, S1, S2, and S3, are to be investigated. The structure and thermal behavior of S1 has already been described in the MDM shown in Figure 2.10. The difference between the candidates is that in S1 a DSP performs the data processing function, while S2 and S3 have an application processor.

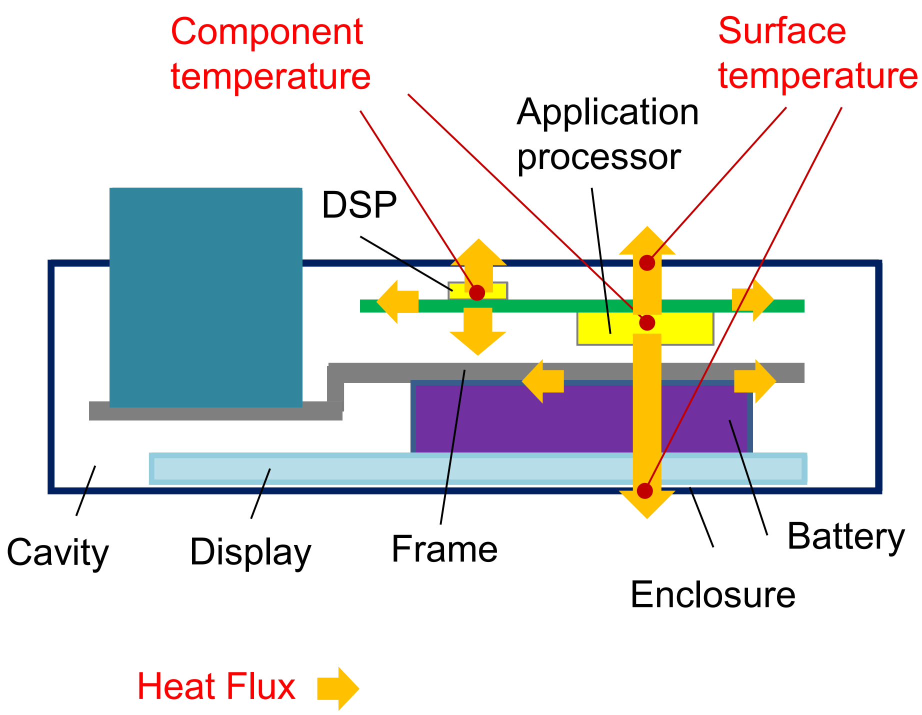


Figure 2.12 Example of the temperature distribution in a digital camera

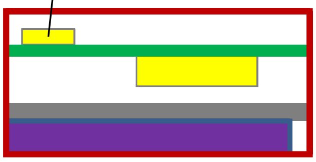
Structure		Temperature		Other concerns
		Component	Surface	
S1	Allocate image processing to DSP 	○	△	- Component cost of DSP - Surface mount are on PWB - Wiring pattern on PWB - Lead-time and difficulty of design changes
S2	Allocate image processing to AP 	X	X	- Software implementation, verification - Power consumption/ Battery Life
S3	Allocate image processing to AP  Install a thermally conductive sheet between AP and frame	△	○	- Software implementation, verification - Power consumption/ Battery Life - Cost and weight of a thermally conductive sheet

Figure 2.13 Examples of architecture candidates

The structure and thermal behavior of S2 are described in the MDM shown in Figure 2.14. The difference in the allocation to DSP is seen from the empty cells in the DSP column and the filled cells in the application processor column. The allocation of the data processing function and related thermal behavior is changed from DSP in S1 to the application processor in S2 and S3. Figure 2.15 shows the TCM of S2. Because of the change in allocation, the application processor temperature increased for S2 because the power consumption of an application processor is higher than that of DSP in S1. The heat generated in the application processor is transferred to both PWB and the cavity. Because the thermal conductivity of air in the cavity limits the amount of heat conducted away, more amount of heat is transferred to PWB than to the cavity. Heat

from the other electrical parts is also transferred to PWB. This concentration of heat hinders to spread heat and reduce peak temperature value around the heat sources.
To compensate for the temperature rise caused by the increased heat generation in S2, a thermally conductive sheet is installed between the application processor and the frame in S3. Figure 2.16 shows the thermal coupling conditions of S3. The new heat transfer path between the application processor and the frame is expressed instead of the path between the application processor and the cavity. Through the new heat transfer path, more amount of heat from application processor to the frame is transferred and spread in the frame than to the cavity in S2.

The MDM descriptions of the architecture candidates enable comparison of ITVs between the candidates in the thermal design view. Table 2.1 s shows an example of the ITVs in the different structure candidates. Each candidate has different ITVs. Different electrical parts, DSP, or the application processor is assigned between S1 and other two candidates. The semiconductor processor is fully activated at each frequency. The heat path from the electrical parts to the mechanical ones and the temperature of the enclosure are also different. The surface temperature of S3 is less than that of the other architectures, and the surface temperature of S1 is also less than that of S2. Therefore, the allocations of functions and thermal coupling affect product temperatures. Considering such variations in allocations helps to generate alternative solutions to satisfy the product thermal quality requirements. In addition to experience in product development, exploration of effective and practical allocation using MDM can help to generate alternatives.

To define architecture candidates, other requirements, including the concerns shown in Figure 2.13, must be considered. In addition to a parts cost for each sample, the S1 candidate requires the surface mount area on PWB and labor costs for wiring the pattern and verification. A longer lead-time and difficulty of design changes for mounting components on PWB are also concerns for this candidate. However, although both component and surface temperatures are higher in S2, the concerns associated with this candidate are fewer than for the others. Concerns also include costs for software implementation and verification and shorter battery life due to increased power consumption. The S3 candidate has a temperature that is lower than that of the others; however, in addition to the same concerns that apply to S2, there are concerns about the cost and weight of a thermally conductive sheet that are unique to S3. The production process for installing the sheet between the application processor and the frame is more flexible in comparison to other candidates in point of design change. In this way, various candidates for the architecture can be compared, and the most affordable candidate can be defined while considering system requirements, including the thermal quality requirements.

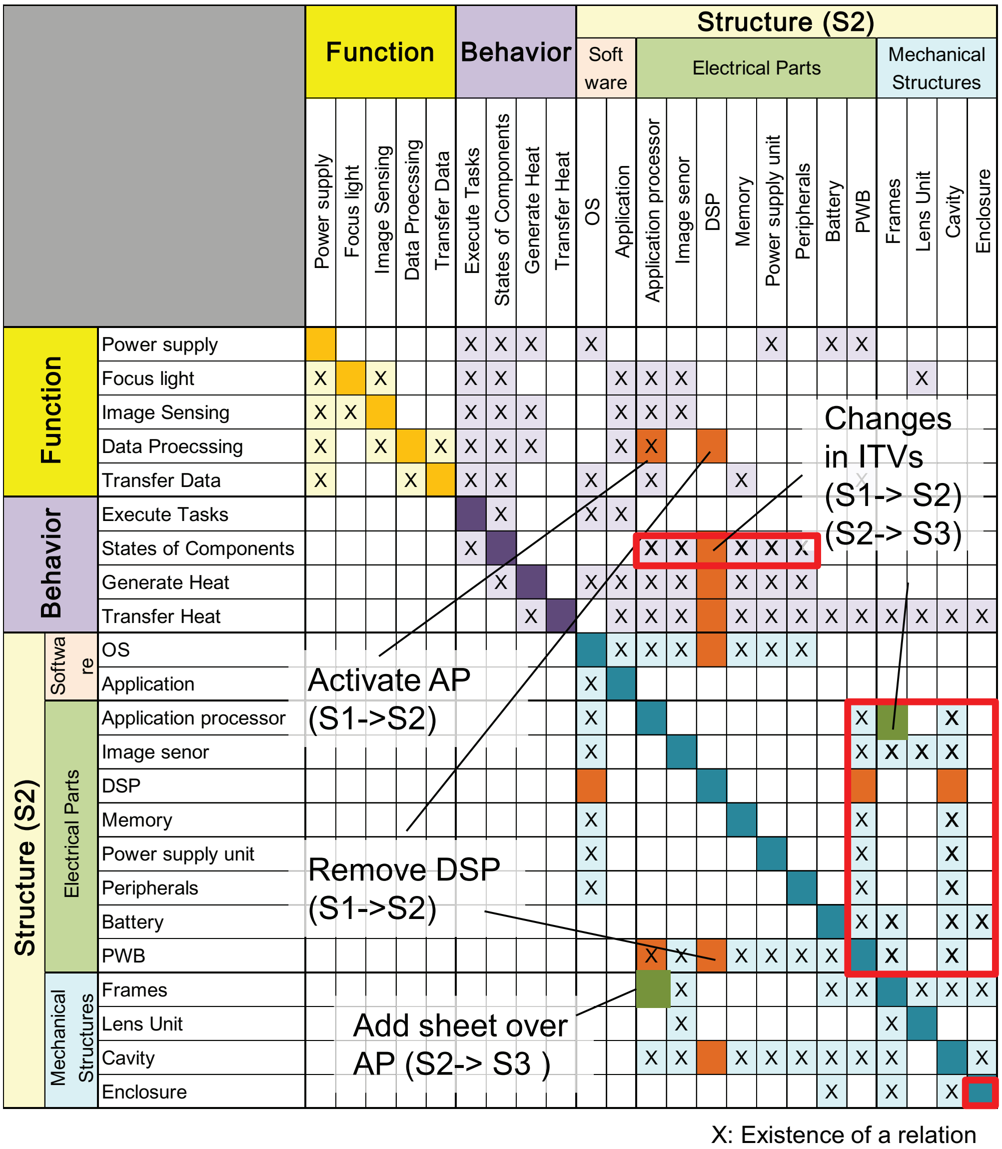


Figure 2.14 Relationships between system elements described in the MDM (S2)

			Structure2 (Hardware S2)											
			Electrical Parts								Mechanical Structures			
			Application processor	Image senor	DSP	Memory	Power supply unit	Peripherals	Battery	PWB	Frames	Lens Unit	Cavity	Enclosure
Structure (Hardware S2)	Electrical Parts	Application processor	90							-0.7			-0.4	
		Image senor		68.8						-0.1	-0.2	-0.1	0.1	
		DSP												
		Memory				69.2				-0.1			-0.1	
		Power supply unit					68.5			-0.3			-0.1	
		Peripherals						60.9		-0.4			-0.1	
		Battery							42	0.2	0.2		-0.2	-0.2
		PWB	-0.7	0.1		0.1	0.3	0.4	-0.2	56	-1.1		-0.3	
	Mechanical Structures	Frames		0.2					-0.2	1.1	54	0.1	-0.3	-1.4
		Lens Unit	0.4	0.1							-0.1	34		
		Cavity		-0.1		0.1	0.1	0.1	0.2	0.3	0.3		53	-0.9
		Enclosure							0.2		1.4		0.9	45

Figure 2.15 Thermal coupling matrix (S2)

			Structure (Hardware S3)											
			Electrical Parts								Mechanical Structures			
			Application processor	Image senor	DSP	Memory	Power supply unit	Peripherals	Battery	PWB	Frames	Lens Unit	Cavity	Enclosure
Structure (Hardware S3)	Electrical Parts	Application processor	84							-0.5	-0.6			
		Image senor		68.3						-0.1	-0.2	-0.1	0.1	
		DSP												
		Memory				68.8				-0.1			-0.1	
		Power supply unit					68.2			-0.3			-0.1	
		Peripherals						60.8		-0.4			-0.1	
		Battery							43.6	0.2	0.2		-0.2	-0.2
		PWB	0.5	0.1		0.1	0.3	0.4	-0.2	55	-1		-0.2	
	Mechanical Structures	Frames	0.6	0.2					-0.2	1	53	0.1	-0.3	-1.4
		Lens Unit		0.1							-0.1	34		
		Cavity		-0.1		0.1	0.1	0.1	0.2	0.2	0.3		53	-0.9
		Enclosure							0.2		1.4		0.9	43

Figure 2.16 Thermal coupling matrix (S3)

Table 2.1 Comparison of ITVs of principal parts for the architecture

	Key electrical part / State (operating frequency)	**Heat transfer from the key electrical part**	**Surface temperature**
S1	DSP / 0.3GHz	0.2 W to cavity	44 °C
S2	AP / 1.0 GHz	0.4 W to cavity	45 °C
S3	AP / 1.0GHz	0.6 W to frame	43 °C

2.3.4 Proposed thermal design process

This subsection describes the proposed thermal design process indicated in the DSM shown in Figure 2.17. During or following the system requirements definition, the system model is developed to determine the required characteristics of the architecture candidates. A system analysis is performed in thermal design view to define the architecture. During the architecture design, the target values of the boundary conditions are defined as ITVs with consideration of the interactions between module design groups. Iteration of these design processes at the concept stage is expected.

After the system architecture is defined with consideration of the system requirements, including the thermal quality requirements, the design of modules progresses based on ITVs. By referring to the design parameters in assessing the architecture candidates, each module design can be detailed to satisfy ITVs. Because the values of ITVs are defined to satisfy product quality requirements using simulation, satisfying ITVs during the module design process assures satisfaction of the product thermal quality requirements. Because the design margins are limited in the thermal design of a portable electronic product and the information contains uncertainty at the concept stage, especially at the early stage of module development, ITVs will most likely be repeatedly updated to adapt to changes in module design. In case an inconsistency is found during the detailed module design, another combination of ITVs is investigated, developed, and updated to satisfy the product thermal quality requirements. To compensate for a lack of communication between the groups independently designing the modules, ITVs are iteratively updated during product development.

This management work of updating ITVs contributes to prevent fatal iterative work that may occur at the time of integration in the late stage of development as described in Figure 1.7. If the product design target is inconsistent in satisfying the product quality requirements, early exploration and system analysis promotes appropriate assistance for efficient development work. Comparison of the alternatives becomes comprehensible for the concerned parties, especially for the module design groups who use MDM to describe interactions between the system elements. Although the module designs are carried out by people from different technological disciplines, monitoring the design progress with ITVs helps to indicate how the module design changes in the thermal design view. Even though software and hardware designs are often performed separately, this dissertation aims to include software design parameters to control the states of electrical parts such as the semiconductor processor. The description of the heat generation behavior using ITVs helps to increase not only the accuracy of the system analysis but also to facilitate managing thermal design parameters in case of design changes.

While product development progresses, the architecture is decomposed. Then the detailed design information is defined for implementation. In accordance with the system analysis planning, the system model can be updated to improve the accuracy of the architecture candidate assessment.

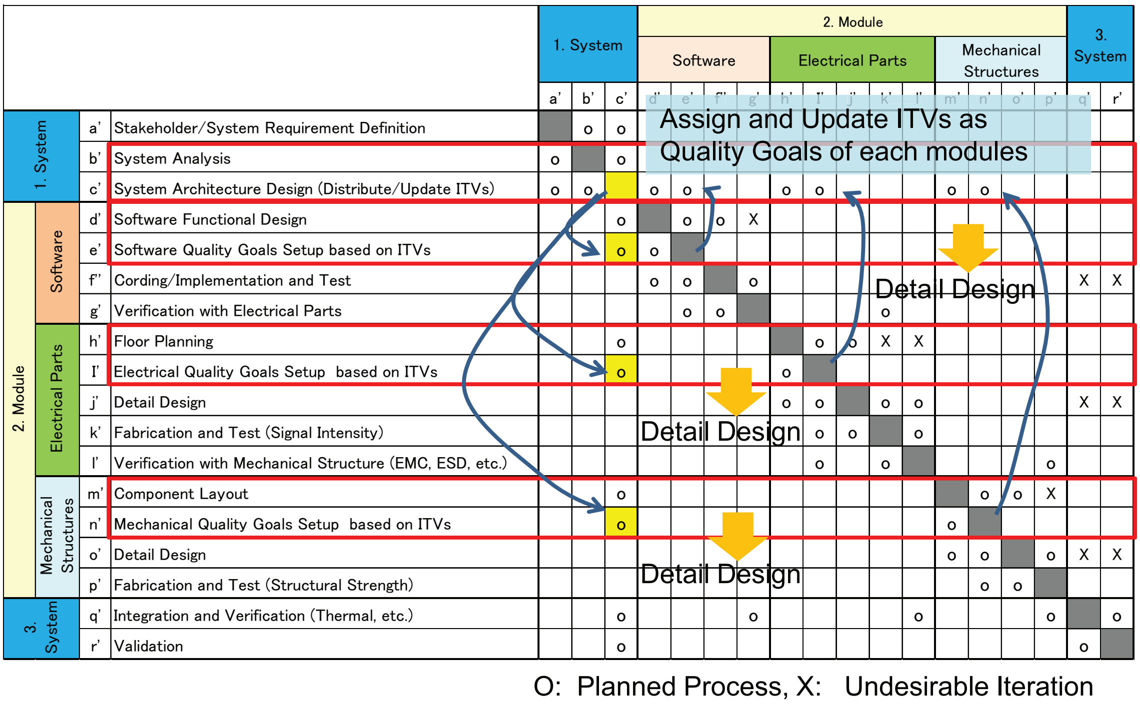


Figure 2.17 Proposed thermal design process for a portable electronic product using ITVs

2.4 Summary

This chapter described the design of the architecture of a portable electronic product in thermal design view. The product consists of modules including software, electrical parts, and mechanical structures within a distributed design environment. To satisfy the thermal quality requirements and prevent fatal iterative work, the system model that describes the behavior of heat generation and transfer was developed consistent with the states of electrical parts to perform the appropriate functions in a particular use case. Equations of behavior for heat generation and transfer were described in the system model in the thermal design view. Using the equations, the temperature rise of the components can be calculated using the design parameters.

The target values (ITVs) for the boundary conditions of the module designs were defined to prevent fatal iterative work during the development. ITVs include the states of electrical parts that are controlled by software, heat transfer from electrical parts to mechanical structures, and the surface temperature of the product. When ITVs are designated for each module design to satisfy product quality requirements, development of the portable electronic product can proceed with cooperation between the module design groups.

In addition, visualizing the relationships between the system elements in thermal design view using MDM was proposed to promote a common understanding between module design groups. MDM comprises the function, behavior, and structure in DSMs. A portion of the structure DSM is designated as the thermal coupling matrix (TCM) to quantitatively visualize the thermal coupling condition. The descriptions of the architecture candidates using MDM and their comparison using ITVs were demonstrated. The author also described the proposed thermal design process expressed in DSM. Throughout the product development process, it is expected that ITVs will be updated to adapt to design changes. This management work of updating ITVs contributes to prevent fatal iterative work at the time of integration. This prevents design changes from occurring at a late stage of development.

Chapter 3

Thermal Design Specification of a Portable Electronic Product

3.1 Introduction

This chapter describes thermal design specification of a portable electronic product. The thermal system is decomposed to describe thermal behaviors of a smartphone. Based on equations of heat generation and heat transfer, thermal simulation is performed to evaluate the thermal quality of the product. Refereeing to a thermal simulation with the conditions under which low-temperature burn injuries occur, this chapter estimates the product thermal quality. Using design parameters, ITVs are calculated as boundary conditions among module designs to satisfy the thermal quality.

The author applies the proposed approach to thermal design specification. First application is parameter exploration for product development. The relationship between two conflicting user requirements, small size and long usage time is quantified to derive thermal design specification of the product. The next application is updating ITVs to prevent degradation of thermal quality due to design changes. The countermeasure alternatives are developed by recalculation of ITVs.

Thermal design using system modeling is also applied to estimate the thermal quality during the support stage. Thermal simulation reflecting expected the states of the electrical parts is performed to prepare countermeasures against further temperature rise caused by software changes.

3.2 Thermal quality of portable electronic products

This research investigates the temperature rise of a simple electronic product. The mechanism for the temperature rise is illustrated in Figure 3.1 In a typical portable product, electrical parts such as semiconductors are affixed to a printed-writing board (PWB), itself fixed to a mechanical structure. As indicated in the figure, the product temperature rises under several activities: activation of semiconductors during the product's operation (a1), dissipation of heat generated in the semiconductor (a2) and transmission of the generated heat to the surface (a3). The software executes in the semiconductor during a product's operation, and the load is processed at a specific frequency. The consumed power is dissipated as heat, implying that heat is generated by operations within the semiconductor.

Temperature increases in electronic products cause various problems such as parts' failure, system defects and burn injuries to the user. Moritz and Henriques (1947) investigated low-temperature burn injuries on human and pig skin. They established the minimum temperature (44 °C) that caused burns over a six-hour contact period. Suzuki and Hirayama et al. (1991) used rats in their investigation, and a temperature of 41 °C is considered to cause burn injuries after touching for five hours. In an effort to prevent such injuries, Roy (2012) referenced the maximum temperatures stipulated in various product standards and suggested the maximum allowable surface temperature for electronic products. Contact temperatures sufficient to cause burn injuries are plotted as a function of time in Figure 3.2

Under constant power consumption, the temperature of an electronic product increases as shown in Figure 3.3 and eventually reaches a steady state. Over a short usage period, the temperature rise will probably not cause low-temperature burn injuries. However, at temperatures as low as 44 °C, users may not regard the product as uncomfortably hot and may unconsciously continue to operate or hold the heated product. Small electronic products such as portable handheld or pocket-carried products can cause low-temperature burn injuries after long-term exposure and under certain operating conditions. In the following thermal design case, the maximum temperature limit depends on the required usage time. The application assumes prolonged usage of an electronic product, such as a video game or movie player, maintaining the surface temperature below 44 °C. The temperature rise time is considerably shorter than the required usage time and is hence ignored.

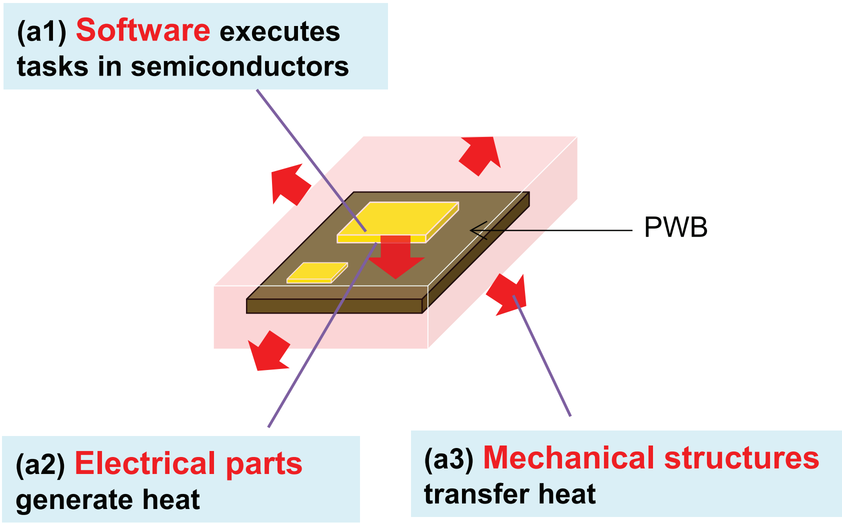


Figure 3.1 Mechanism of temperature rise in an electronic product

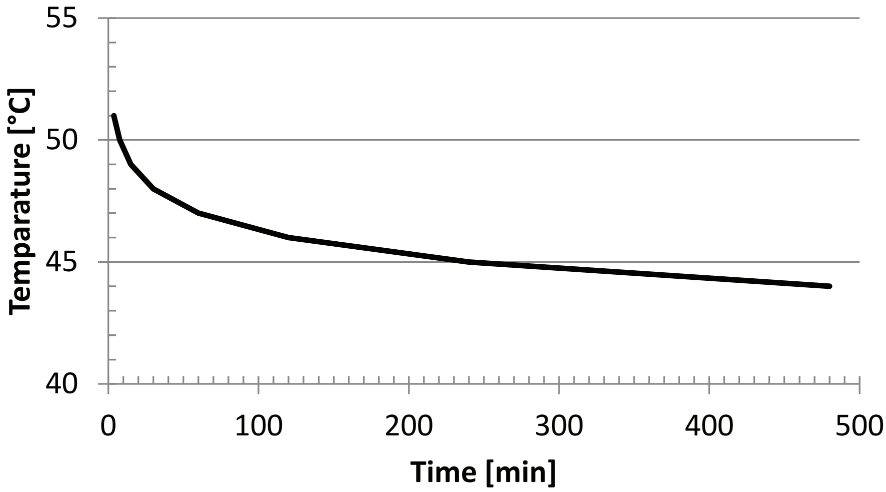


Figure 3.2 Temperature causing low-temperature burn injuries as a function of contact time (Moritz and Henriques, 1947)

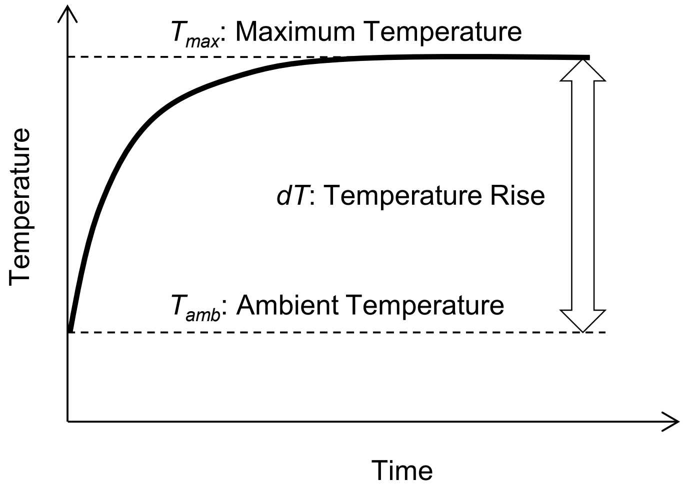


Figure 3.3 Typical temperature rise curve

3.3 Development of the system model for smartphone thermal design

This section describes behaviors of heat generation and transfer for smartphone thermal design. The thermal system is decomposed to express the behaviors of a portable electronic product that has a simple structure. Then the simulation model is developed based on the equations in the system model to estimate the temperature rise. The equations include the design parameters of the module design and ITVs, which constitute boundary conditions between the modules. Figure 3.4 illustrates the activities of the thermal system of the product shown in Figure 2.5. First, tasks are allocated in a product running a certain application. The tasks are scheduled in the OS and executed to process the load-assigning frequency (a1-1), manage the supply power, including charging (a1-2) and configure the peripherals' states during operation (a1-3). The task execution generates heat in the processor (a2-1), power management ICs (a2-2) and peripheral devices, including the driver ICs of peripherals (a2-3). In a typical portable product, the semiconductors are affixed to a PWB as shown in Figure 3.1. Because the PWB contains thermally conductive materials such as copper, the generated heat is assumed to transfer first to the PWB (a3-1) and then through the mechanical structures to the product surface, where it is dissipated into air.

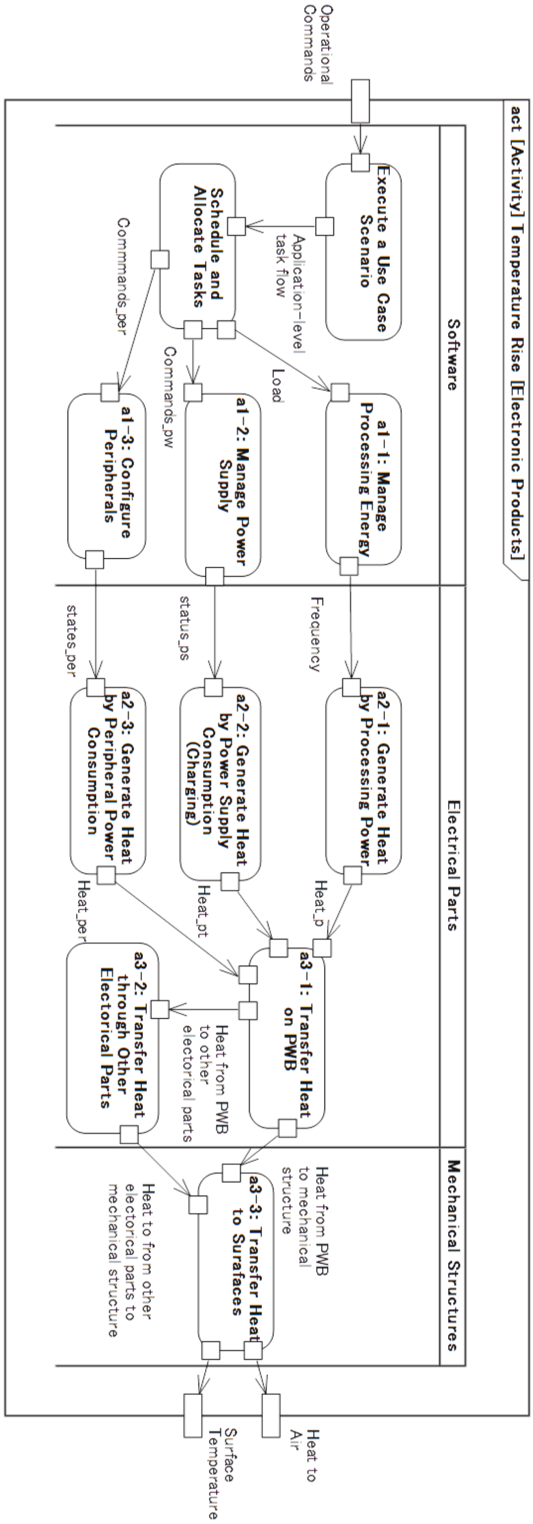


Figure 3.4 Activity diagram of temperature rise in an electronic product

To suppress temperature rise on the product surface, reduction of the processing power must be discussed. Various approaches such as dynamic thermal management (Brooks, 2001) have been proposed for this purpose. The aim is to limit the temperature increase without compromising the product performance. The temperature of a processor can be monitored by an internal thermal sensor. When the temperature exceeds some trigger level, the frequency and/or voltage is scaled down to reduce the processing power. The heat dissipated in a processor is proportional to its power consumption, as described below.

$$Q_p = C_l \cdot F \cdot V^2 \tag{3.1}$$

In Eq. (3.1), C_l is the physical semiconductor capacitance, and the voltage V and frequency F are simplified and based on the switching power dissipation behavior of the CMOS (Chandrakasan et al., 1992). In addition, a processor is assumed to be fully activated at the specified frequency. However the dynamic thermal management can suppress rapid temperature rise, a processor is being fully activated at the constant load during prolonged applications. For such applications, it is insufficient to suppress temperature rise on the product surface. In the present study, behaviors of electrical parts including a processor are modelled. Considering constraints of heat generation of electrical parts and heat transfer of mechanical structures, design parameters of the thermal system are balanced to satisfy the product thermal quality. The (simplified) total heat dissipation Q of the product is given by

$$Q = Q_p + Q_{chg} + Q_{per} \tag{3.2}$$

where Q_{chg} is the heat dissipation induced by the voltage conversion loss when a product is operated during battery charging and Q_{per} is the power consumption of peripheral components such as the driver ICs of the display. Because heat is transferred to the PWB, we consider that all heat generated in the product is distributed over the PWB with equal density.

The surface temperature is calculated by a similar heat transmission equation. Figure 3.5 shows the dimensions of the electronic product modelled in the present study. The outer dimensions are the length l, width w and thickness t. The structural parts are simplified as two blocks located at the top and bottom, with thicknesses t_1 and t_2, respectively.

Because the generated heat is dispatched from the product surface to air, the temperature rise strongly depends on the surface area.

Figure 3.6 illustrates the heat transmission in a cross-sectional view of the product. The heat generated at the boundary between the top and bottom parts is dispatched to the ambient air through the top and bottom surfaces. This heat transmission can be described by thermal network analysis. Thermal resistance, defined as the ratio of the temperature difference at an object's interface to the heat transfer through the object, is here defined in two ways. First, the resistance between the product surface and ambient air is described as

$$R_{s\_i} = 1 / (h \cdot A_{s\_i}) \qquad (3.3)$$

This equation involves the heat transfer coefficient h and the surface area A_{s_i}. h is regarded as constant, and the surface area A_{s_i} is that specified in Figure 3.5. The subscript i of the variables mean the positions. If i equals 1, the variables are belongs to the top part of the object. If i equals 2, the variables are belongs to the bottom part of the object. A_{s_1} is surface area of the top part for example. The thermal resistance within the product is given by

.

$$R_{in\_i} = 1 / (\lambda_i \cdot l \cdot w / t_i) \qquad (3.4)$$

which depends on the above-stated parameters and a material property called thermal conductivity (λ_i). In this study, the conductivity of the simplified structure is estimated by its equivalent value. The conditions of heat transfer are considered as horizontally uniform.

Because the generated heat is dispatched from both sides of both surfaces, the calculation includes four thermal resistances: R_{s_1}, R_{in_1}, R_{in_2} and R_{s_2}. The surface temperatures are estimated as

$$T_{s\_i} = Q_i \cdot R_{s\_i} + T_{amb} \qquad (3.5)$$

where the heat transfer Q_i is the generated power to be dispatched from one side of the surface and T_{amb} is the ambient temperature.

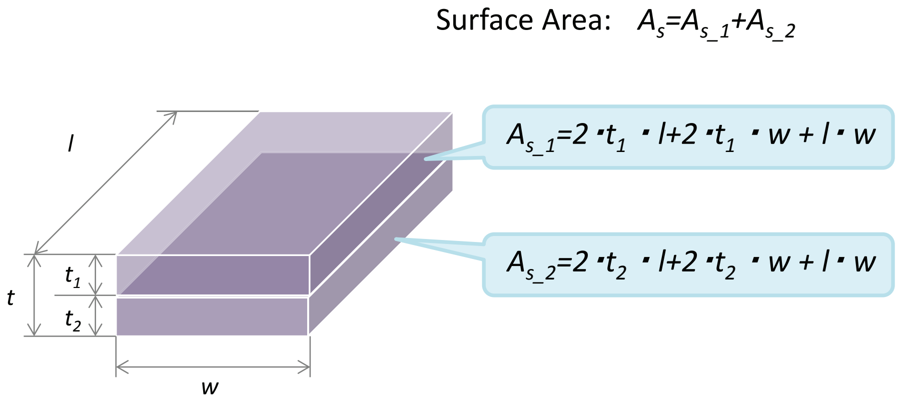


Figure 3.5 Dimensions of a simplified electronic product

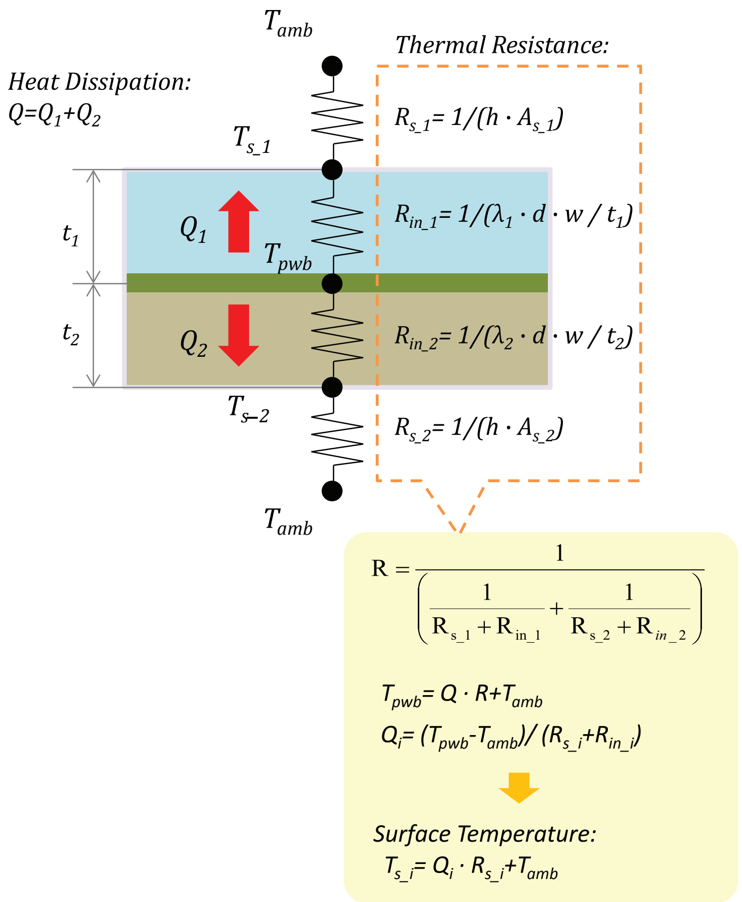


Figure 3.6 Heat transmission through the cross-section of a simplified electronic product

The block diagram of Figure 3.7 describes the actives and constraint relations in the thermal system of the electronic product model. Shown are the activities of the thermal system and their relations with the thermal constraints. As a design constraint, the software that controls electrical parts should optimally operate at the specified processing frequency, power management states (including charging) and peripherals. Using the above equations, the author constrains the heat generation and transmission in the system. To ensure high thermal quality of the product, the activities are moderated by the constraints.

In SysML, whether the constraints are satisfied is decided from a parametric diagram. The calculation of the surface temperatures T_{s_1} and T_{s_2} from the design parameters is shown in Figure 3.8. The design parameters are assigned to their values in the module design. The product operating conditions (including processing frequency and states of battery charging), design parameters related to heat generation and parameters related to heat transmission are assigned by the software, electrical and mechanical designs, respectively.

Using thermal simulation, design parameters to satisfy system requirements including the product thermal quality are being explored. After the appropriate design parameters are defined, the boundary conditions among modules are determined as ITVs. ITVs consist of the states of the electrical parts, heat and temperature. Because the physical structure is simple, sum of transferred heat is regarded as ITVs for the smartphone thermal design in this chapter. Each module with its design parameters is designed to satisfy a target ITVs. The ITVs are updated until the constraints, and thereby the target thermal quality, are satisfied. To estimate the impact of design change, the effect of each module design is evaluated in thermal simulations. The parameter range satisfying the thermal quality can be investigated by changing the internal design parameters of each module and recalculating the ITVs.

Figure 3.9 illustrates relationships between function, thermal behaviors and structures of the portable electronic product using a MDM. Using the matrix, system elements that affect the temperature rise are described. This visualization promotes comprehension of interactions of the system elements among concerned parties including module design groups. The MDM is to be applied for comparison between countermeasure alternatives as described later.

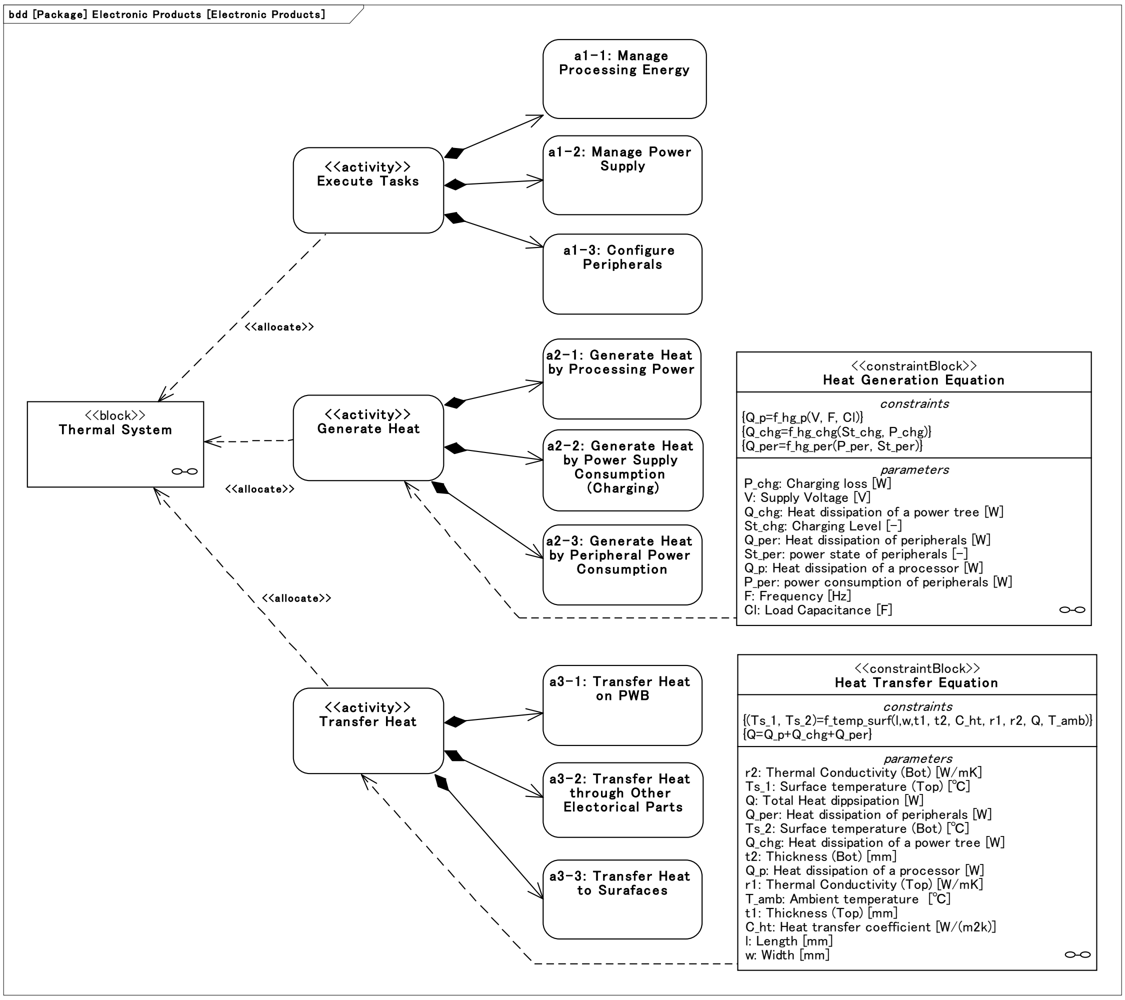


Figure 3.7 Activity and constraint relations of heat generation and transfer

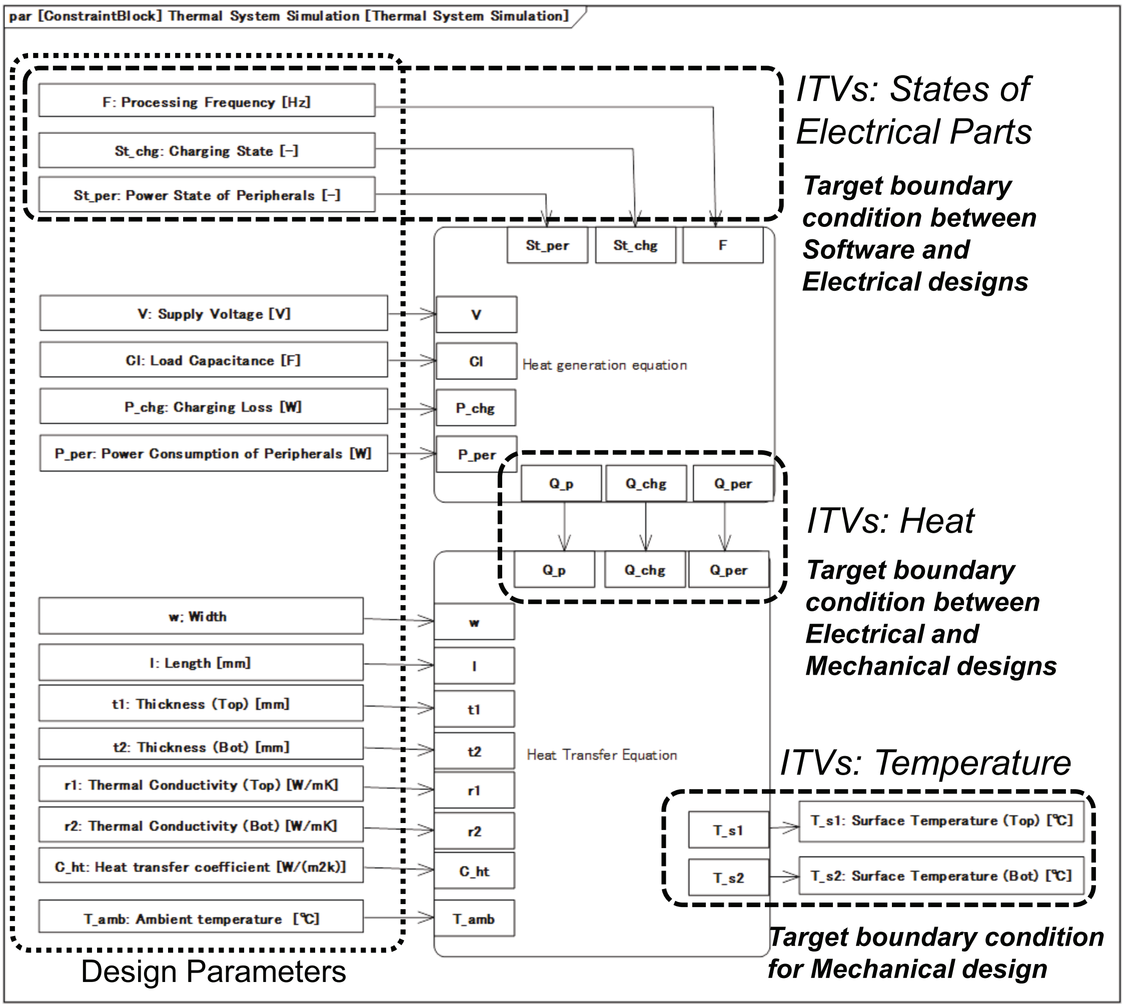


Figure 3.8 Parametric diagram of temperature constraint

			Function					Behavior				Structure									
												Software		Electrical Parts					Mechanical Structures		
			Power Supply	Charging	Sensing	Data processing	Display	Execute Tasks	States of Components	Generate Heat	Transfer Heat	OS	Application	Processor	Power supply unit	Peripherals	Battery	PWB	Frames	Cavity	Enclosure
Function		Power Supply		X				X	X	X		X			X		X	X			
		Charging	X			X		X	X	X		X			X		X				
		Sensing	X	X		X	X	X	X	X			X	X		X					
		Data processing	X		X		X	X	X	X			X	X							
		Display	X		X	X		X	X	X			X			X					
Behavior		Execute Tasks							X			X									
		States of Components						X				X		X	X	X					
		Generate Heat							X					X	X	X					
		Transfer Heat								X				X	X	X	X	X	X	X	X
Structure	Software	OS											X	X	X	X					
		Application										X									
	Electrical Parts	Processor										X						X		X	
		Power supply unit										X						X		X	
		Peripherals										X						X		X	
		Battery																X		X	X
		PWB												X	X	X	X		X	X	
	Mechanical Structures	Frames																X		X	X
		Cavity												X	X	X	X	X	X		X
		Enclosure															X		X	X	

X: Existence of a relation

Figure 3.9 Relationships between system elements of a smartphone described in MDM

3.4 Application to thermal design in the development stage

3.4.1 Thermal design parameter exploration to resolve conflicting user requirements

The thermal simulation model based the system model is applied to explore the design parameters that resolve conflicting user requirements of a portable electronics product. This subsection describes improvement of the design parameters in case that the initial conditions do not resolve the conflicting user requirements. The author discusses the benefits of this approach in a product development context.

In the application, a small-size electronic product is designed to satisfy the user requirements. The initial design parameters, from which the surface temperatures are calculated, are listed in Table 3.1. The top part consists of various devices such as display and speaker, as well as an air gap for assembly tolerance. The bottom part consists of hardware such as PWB, semiconductors and battery. These electrical parts contain materials of high thermal conductivity, such as copper and carbon. The thermal conductivity of each part is assigned an equivalent composite conductivity of the various materials.

Then the simulation based on the system model is performed using the parametric model in Figure 3.8. The user requirements are small size and long usage time. The first requirement stipulates that the thickness t is less than 15 mm to ensure portability, while the usage time (is more than 3 hours) is sufficient to watch a streamed movie. As shown in Figure 3.10, the surface temperatures are calculated assuming the initial design parameters in Table 3.1 and varying thickness of the bottom part, t_2. The allowable usage time is approximated from the temperature curve of Figure 3.2.

As shown in Figure 3.10, the allowable usage time for a 15-mm-thick product is less than 180 min, implying that the requirements are not satisfied. Because the temperature of the bottom surface exceeds that of the top surface, the allowable usage time is based on the bottom surface temperature.

Table 3.1 Initial design parameters

Software	F	1000 MHz
Electrical Parts	C_l	0.4 μF
	V	2 V
	Q_{per}	1.2 W
Mechanical Structures	l	100 mm
	w	50 mm
	t_1	7 mm
	h	11 W/(°C·m^2)
	λ_1	0.1 W/(°C·m)
	λ_2	2 W/(°C·m)
Environment	T_{amb}	25 °C

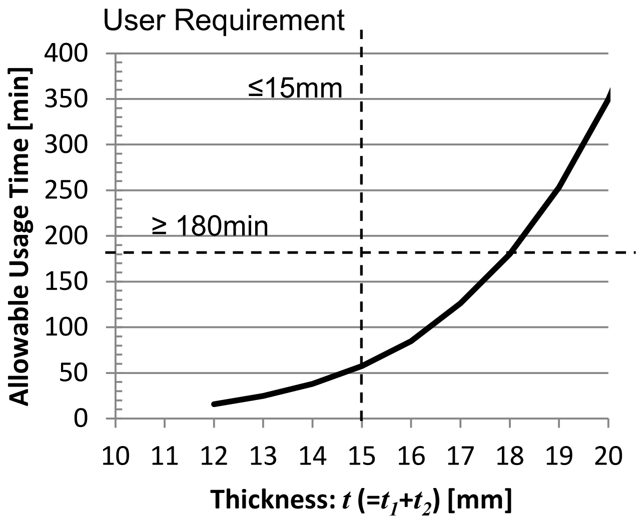


Figure 3.10 Simulation result assuming initial parameters listed in Table 3.1

To satisfy the user requirements, the author proposes countermeasure alternatives for extending usage time without incrementing the thickness. Two countermeasure alternatives are shown in Table 3.2. First, the power Q in the ITVs is reduced by alternative semiconductor and circuit design that operates at lower voltage. Relationship between power Q and allowable usage time is shown in Figure 3.11. As the power Q decreases, the surface temperature on the bottom surface T_{s_2} goes down and the allowable usage time increases. In case that thickness of that product t is 15 mm and other design parameter is same as the initial parameter in Table 3.1, power Q must be lower than 2.6 W to satisfy the 180 min usage time. If the voltage of semiconductor voltage can be reduced from 2.0 to 1.8 V, the power Q in the ITVs decreases to 2.5 W. Correspondingly, the surface temperature T_{s_2} decreases to accommodate the allowable usage time. The results of the calculation are shown in Figure 3.12.

The second alternative is to reduce the surface temperature T_{s_2} in the ITVs by changing the mechanical structures, for example, by filling the air gap in the top part by a soft thermal interface material (TIM). Relationship between the thermal conductivity of the top part λ_1 and allowable usage time is shown in Figure 3.13. As the thermal conductivityλ_1 increases, more amount of heat is dispatched from the top surface. Then, the surface temperature on the bottom surface T_{s_2} goes down and the allowable usage time increases. In case that thickness of that product is 15 mm and other design parameter is same as the initial parameter in Table 3.1, the thermal conductivity λ_1 must be more than 0.17 W/(°C·m) to satisfy the 180min usage time. If the thermal conductivity of the top part λ_1 is increased from 0.1 to 0.25 W/(°C·m), similar to the conductivity of a resin, and the surface temperature of the bottom T_{s_2} reduces to accommodate the allowable usage time. As shown in Figure 3.14, this alternative also extends the allowable usage time without increasing product thickness.

The coupled calculations do not require complicated models. In this module-based approach, changes to the design of a proposed product can be readily discussed among concerned parties using alternatives generated by changes within each module. Because the architecture candidates that are traceable to the system model are defined, the most appropriate candidate can be selected. The benefit of coupling is to quantify the conflicting requirements. If the alternatives are disadvantageous; for example, if they incur a cost increase, the most practical solution can be identified through discussion with personnel involved in product engineering, design, planning and purchasing. Once the design change has been planned and the ITVs defined, the modified design is executed within each module. Because they require different engineering skills and knowledge, module are typically designed by different team within an organization. However, if each module is designed to meet specified ITVs, collaborative product development becomes possible. Resolving conflict in the early stage of development reduces the required number of redesign of the thermal management specifications.

Table 3.2 Countermeasure alternative for the parameter exploration

		Initial	Countermeasure	
			Alternative 1	**Alternative 2**
The module to change design		-	Electrical Parts	Mechanical Structures
Changed design parameter		-	V: 2.0-1.8 V	λ_l: 0.1-0.25 W/(°C·m)
Simulation result (t=15mm)	ITV F	1000 MHz	1000 MHz	1000 MHz
	Q	2.8 W	2.5 W	2.8 W
	T_{s_1}, T_{s_2}	37.9, 47.1 °C	36.5, 44.6 °C	40.5, 44.5 °C
	Allowable usage time	57 min	307 min	332 min

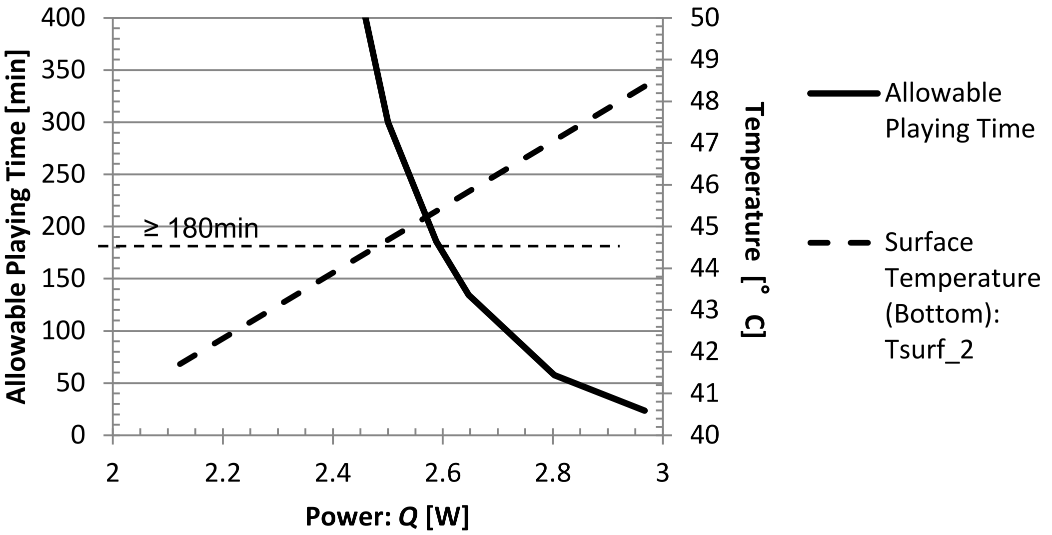


Figure 3.11 Relationship between power and allowable playing time (Thickness: t = 15mm)

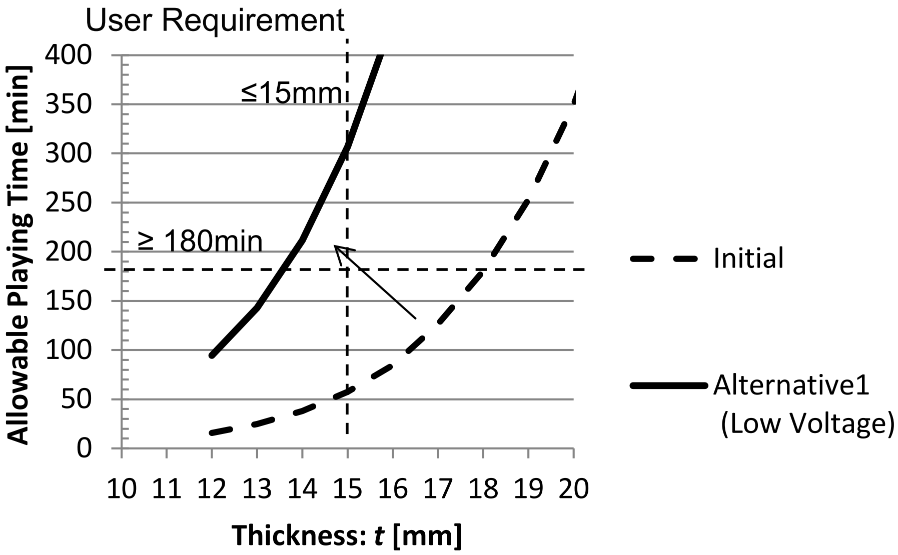


Figure 3.12 Simulation result of alternative 1 (reducing power consumption in the ITVs)

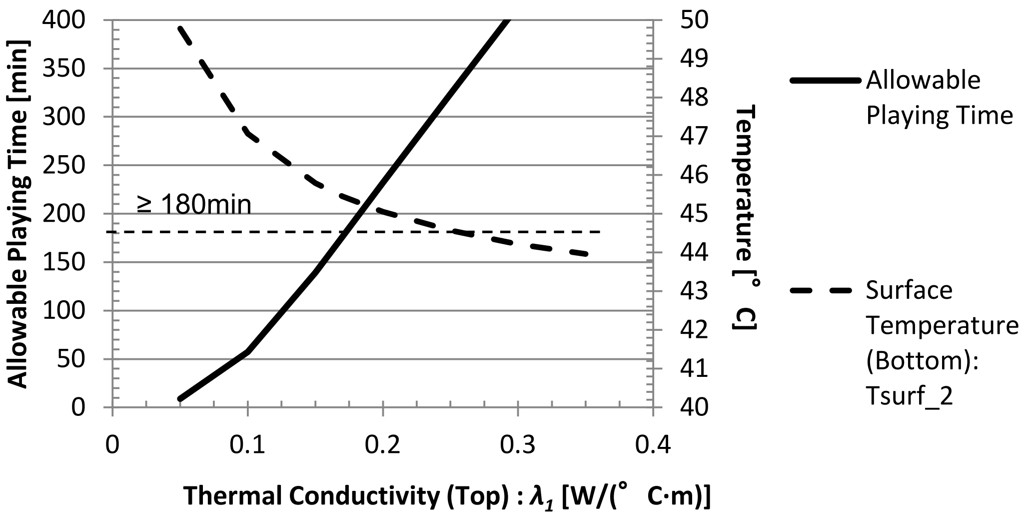


Figure 3.13 Relationship between thermal conductivity of top part and allowable playing time (Thickness: t = 15 mm)

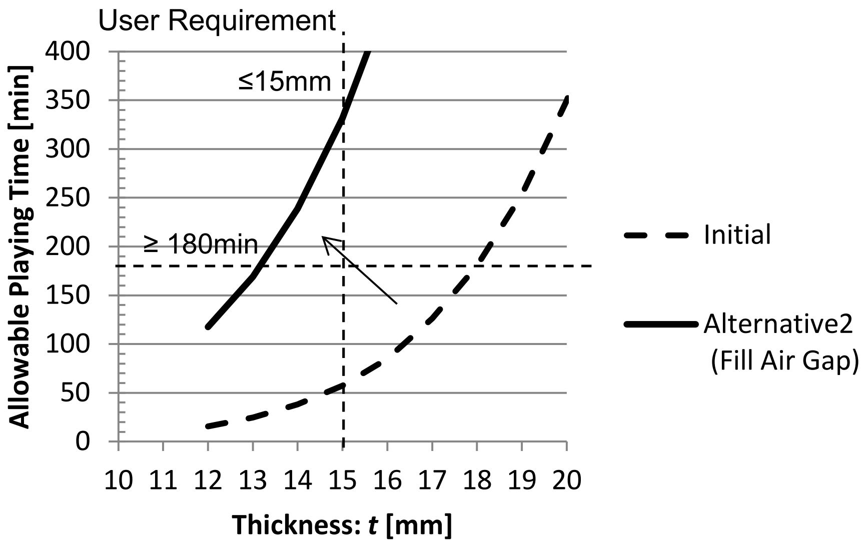


Figure 3.14 Simulation result of alternative 2 (reducing temperature at the bottom surface)

3.4.2 Update ITVs to prevent degradation of thermal quality due to design changes

Applying the thermal simulation model based on the system model, the specification of electronic products can be derived to satisfy constraints in order to prevent burn injuries for two applications. After calculation of initial design parameters, the simulation based on the system model is again used to propose countermeasure alternatives for improvement. In this subsection, the author discusses the benefits of this approach in the case when the design change involves addition of an application.

A small-size electronic product is designed with constraint to prevent burn injuries. Two semiconductor processors are installed on it as electronics parts. Q_{p_1} and Q_{p_2} are the powers of the semiconductors, and the power of the system is the sum of Q_{p_1} and Q_{p_2}, as described as Eq. (3.6).

$$Q_p = Q_{p\_1} + Q_{p\_2} \tag{3.6}$$

In Eq. (3.6) that describes the power dissipation of the CMOS, Q_{p_1} and Q_{p_2} are described using Eq. (3.7) and (3.8).

$$Q_{p\_1} = C_{l\_1} \cdot F_1 \cdot V_1^2 \tag{3.7}$$

$$Q_{p\_2} = C_{l\_2} \cdot F_2 \cdot V_2^2 \tag{3.8}$$

Table 3.3 shows the initial design parameters, which are the design parameters and ambient temperature, for instance. Each semiconductor processor has a different role, such as CPU or GPU. Heat transfer coefficient has equal value of all sides of product surface in natural convection. ITVs that are frequency *F*, power *Q* and temperature rise *dT* are calculated in following subsection.

In this subsection, two applications, A and B, are assumed such as video games and video encoding. The frequency *F* of ITVs is determined for two semiconductor processors. Then, the remainder of ITVs is subsequently calculated as shown in the parametric model in Figure 3.8. The first calculation of ITVs is shown in Table 3.4. To eliminate the possibility of burn injuries, the surface temperature *T* must be below 44 °C in this application. Though number of design changes for improvement should be limited. Iterative work is preferred as small as possible after the product development is started. As shown in the table, the surface temperature *T* of application A is 43.1 °C which is lower than the temperature target. However, application B has different ITVs for frequency, and the surface temperature *T* of application B is 45.6 °C, which is higher than the target; moreover, a user can be burned during operation. Figure 3.15 shows the variation of temperature required to cause burns, as shown in Figure 3.2, and the calculated surface temperatures of two applications are indicated. As shown in the figure, there is a risk of burn if a user operates application B while touching the product for more than 180 min.

Then, the author proposes countermeasure alternatives the temperature of application B by recalculating ITVs. Three alternatives are shown in Table 3.5. First, the software is designed for execution at lower frequency, which provides less processing power (Venkatachalam and Franz, 2005). If the frequency of semiconductor1 F_1 is reduced from 700 to 550 MHz, the surface temperature *T* decreases to 42.5 °C, which is within the target. Second, the power *Q* in ITVs is reduced by changing semiconductor and circuit design in order to adapt for operating at lower voltage. If the voltage of semiconductor2, V_2, can be reduced from 3.6 to 2.7 V, the power Q in ITVs decreases to 1.12 W. Then, the surface temperature T also decreases to 43.0 °C, which is within the target. The third alternative is that the temperature rise dT in ITVs is reduced by changing the mechanical structures, thereby expanding the product size. If the thickness of the dimensions of the enclosure is extended from 10 to 14 mm, the surface area A_s increases. Then, the surface temperature T also decreases to 43.2 °C, which is within the target.

Those coupling calculations do not require complicated models. With the system design approach among modules, design changes can be discussed using the proposed alternatives that have changes in each module. After countermeasure alternatives are generated by adjusting design parameters of the modules, the most practical solution can be identified. Because values of ITVs are determined to satisfy product quality, satisfaction of ITVs in module designs assures the product thermal quality after the design changes.

Table 3.3 Initial design parameters before the design change

Semiconductor 1	C_1	0.1 μF
	V_1	3.6 V
Semiconductor 2	C_2	0.065 μF
	V_2	3.6 V
Mechanical Enclosure	A_s	35×50×10 mm
	h	12 W/(°C ·m^2)
Environment	T_{amb}	25 °C

Table 3.4 Calculation results of application A and B

Application	A	B
ITV F_1	820 MHz	700 MHz
F_2	80MHz	450 MHz
Q	1.13 W	1.29 W
dT	18.1 °C	20.6 °C
Surface temperature T	43.1 °C	45.6 °C
Possibility to be burned	No	Yes (over 180 min usage)

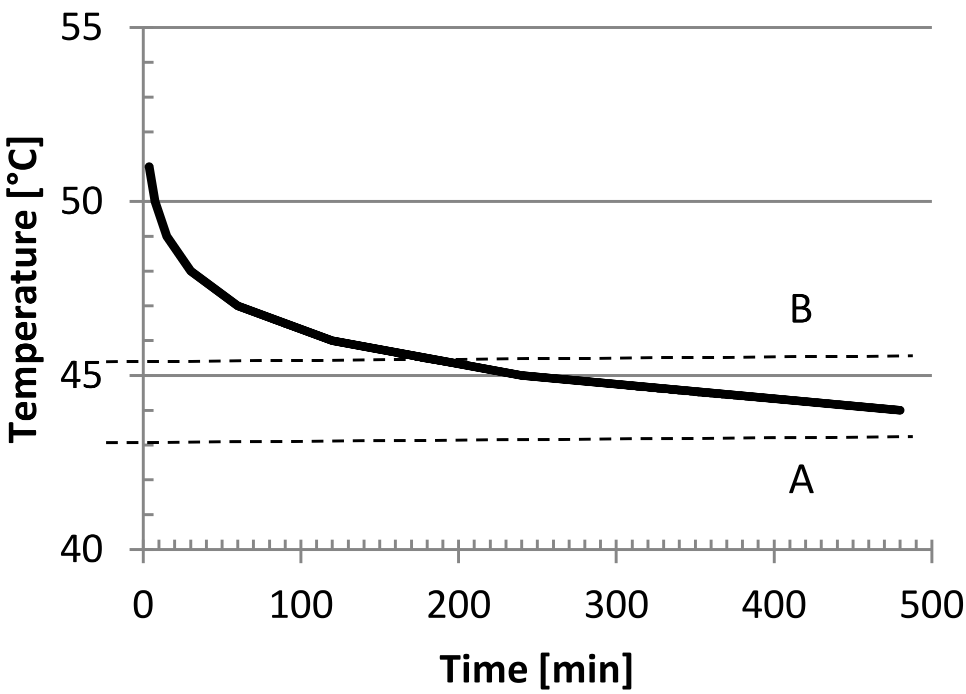


Figure 3.15 Thermal risk of applications A and B

Table 3.5 Countermeasure alternatives to improve the surface temperature of application B

	Initial (Application B)	Countermeasures		
		Alternative 1	**Alternative 2**	**Alternative 3**
The module to change design	-	Software	Electrical Parts	Mechanical Structures
Changed design parameter	-	F_1: 700 -> 550 MHz	V_2 : 3.6 -> 2.7 V	A_s (Thickness): 10mm -> 14mm
ITV F_1	700 MHz	550 MHz	700 MHz	700 MHz
F_2	450 MHz	450 MHz	450 MHz	450 MHz
Q	1.29 W	1.09 W	1.12 W	1.29 W
dT	20.6 °C	17.5 °C	18.0 °C	18.2 °C
Surface temperature T	45.6 °C	42.5 °C	43.0 °C	43.2 °C
Possibility to be burned	Yes (over 180 min usage)	No	No	No

3.5 Application to thermal design in the support stage

3.5.1 Thermal management in a maintenance process

Besides the development stage, thermal design must be considered in the support stage of an electronic product's lifecycle. Once the hardware development is complete, the product will be repeatedly exposed to software changes such as updates or the installation of new applications. Post-purchase installation of software, including applications and new OSs, now constitutes the bulk of product variation (Kuusela, 2012). As shown in Figure 1.9, official version of Android OS is released about several times a year. In addition, the number of available Android applications has already reached one million in 2013 (Google, 2013). At the time of product maintenance during the support stage, additional hardware implementations are not available and the number of hardware engineers is usually limited. However, if a software algorithm varies the load on electrical parts such as a processor, the software updates incur thermal risk to the electronic products.

Once the product design specifications have been derived through architecture design, the system outline is checked in detail, decomposing its elements into physical specifications. In general, the software, electrical parts and mechanical structures are developed by different engineering groups. As shown in Figure 3.16, the modules are developed in parallel. However, to ensure that the system functions satisfy the requirements, verification is required. Thermal verification is often performed through thermal simulations and temperature measurements, particularly during module development. Before mass production, the designed modules are integrated into physical prototypes, and their quality is assured by temperature measurements. In case that thermal problem is found at verification in the late stage of the development, iterative work will be fatal to maintain the development schedule. Modules that fail these tests should be improved as soon as possible. Considering that the progress levels of modules vary during their developments, verifications must be performed at the correct time.

Software also changes during the support stage, i.e. after the hardware development is completed. As cited above, most of the product variation now occurs post-distribution. Because many features of electronic products are flexibly implemented by software, product complexity is continually increasing (Siemens, 2012). Therefore, a product must be verified after any design change, including software changes. The thermal simulation model in the present study verifies the product in both the development and support stage of the product lifecycle.

In contrast that the above-mentioned thermal design approaches were aimed to derive design specifications in the development stage, this subsection investigates the thermal safety of the product by efficient thermal management during the support stage. In the support stage, the author aims to evaluate thermal risk of software changes and prepare countermeasure alternatives even when no post-distribution hardware solution is available. Measures to prevent temperature rise are limited. In addition, verification resources are also limited after development in general. Corresponding to the difficulties of thermal design during the support stages, the author employs the thermal simulation model, coupling the activities within modules including the software.

The thermal design in this subsection uses system models developed during the development stage. The DSM in Figure 2.17 shows the postulated design process using the system model. To implement this process, the author introduced the design approach using ITVs. In the early stage of the development stage, the ITVs are calculated to satisfy these requirements. The assigned ITVs are then used in the module design.

To manage thermal quality in the support stage, the system model that developed in the development stage is applied reflecting expected thermal behaviors. Once the hardware development is complete, software changes such as OS upgrade continue in the support stage. Figure 3.17 illustrates the proposed maintenance process using the system model. The outline of the software change is determined in the maintenance planning, and the thermal risk is estimated from the calculated ITVs. The estimation is based on the system model that used in the development phase, or can be updated to more accurately simulate.

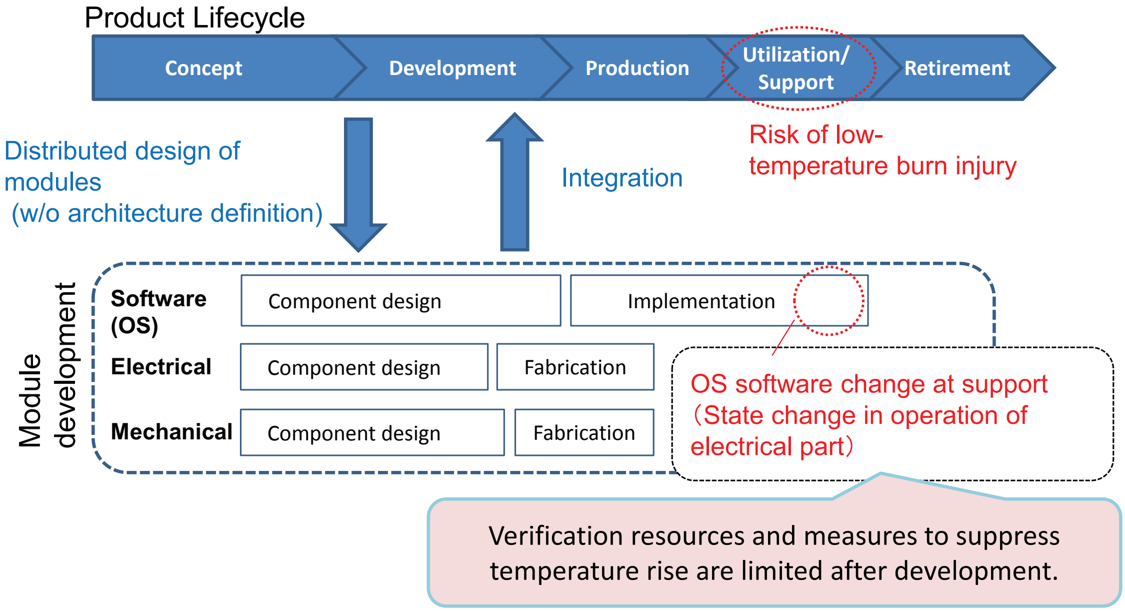


Figure 3.16 Thermal problem in the support stage of lifecycle

			1. System			2. Module Software				3. System (Varied)				
			a'	b'	c'	d'	e'	f''	g'	s'	t'	u'	v'	w'
1. System	a'	Product Positioning and Business Analysis		o	o									
1. System	b'	System Analysis	o		o						o			
1. System	c'	System Architecture Design (including ITVs)	o	o		o	o				o			
2. Module Software	d'	Software Functional Design			o		o	o	X		o			
2. Module Software	e'	Software Quality Goals Setup based on ITVs			o	o					o			
2. Module Software	f''	Cording/Implementation and Test				o			o	X		o		
2. Module Software	g'	Verification with Electrical Parts					o	o				o		
3. System (Varied)	s'	System Analysis with varied ITVs							o		o			
3. System (Varied)	t'	Maintenance Planning			o					o		o	X	
3. System (Varied)	u'	Modification Implementation									o		o	
3. System (Varied)	v'	Quality Assurance Testing							o		o	o		
3. System (Varied)	w'	Migration											o	

Detail Soft. Design

Maintenance

③Software Change

① Update the system model

② Calculate ITVs to evaluate risk of Software Change

Figure 3.17 Thermal management process for a software changes in the support stage

The effect of the software change on the ITVs can be regarded as a change in processor frequency, which is equivalent to changing the load of the task execution. Other power-estimation techniques can also be used. The effects of software changes can also be investigated by bytecode profiling (Hao et al., 2012) and modeling of component behavior in various applications (Zhang et al., 2010). If the software prototype is available, the power consumption can be measured on the developed hardware.

Because temperature measurements consume preparation and data sampling time during the temperature rise, one analysis usually takes a few hours. Therefore, by adopting the system design approach to thermal risk filtering, considerable time and effort in the verification can be saved. As shown in Figure 3.18, the verification is first performed using thermal simulation to evaluate if the behavior of new software causes temperature rise that exceeds the target. If it is regarded as fail, temperature measurement or detail simulation can be performed to examine the degradation of thermal quality. If the temperature rise is still regarded as a risk, thermal mitigation or need of the software change must be investigated. Simulation based on the system model is based on simple and fast calculations and admit unlimited measurements (except in critical cases). After the hardware development, the number of hardware engineers or verification teams may be insufficient to meet the demand, risking insufficient verification in the support stage.

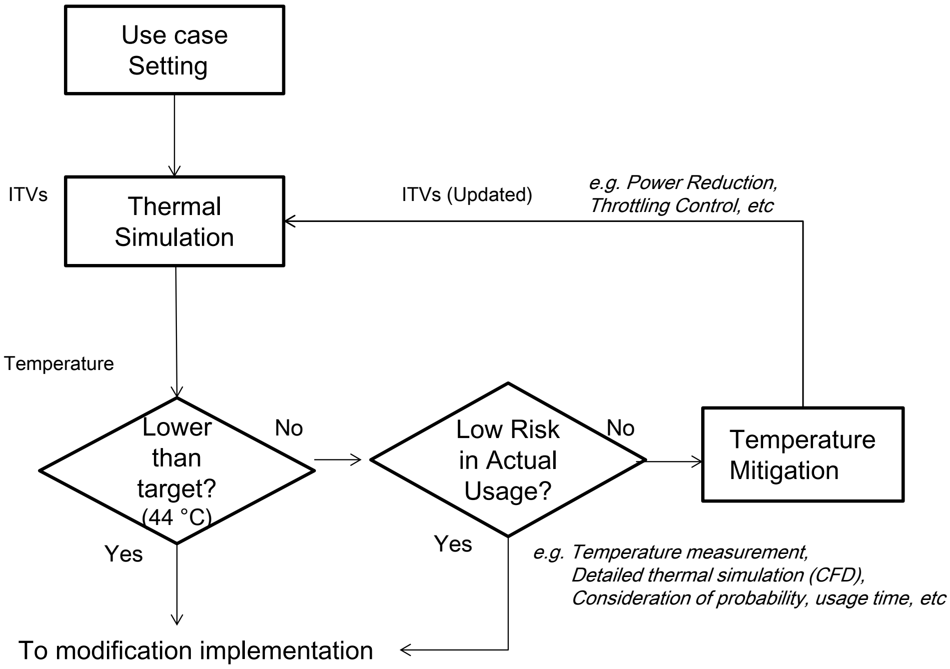


Figure 3.18 Verification workflow

3.5.2 Estimation of thermal quality in preparation for software changes

In the application, the author defines the specifications of electronic products that must not exceed the target temperature. To prevent burn injuries, the surface temperature should be below 44 °C (Moritz and Henriques, 1947). The initial design parameters for small-size electronic products are listed in Table 3.6. The thermal conductivities of the simplified structure are estimated by their equivalent values. The top part of the product comprises various components such as display and speaker and an air gap for assembly tolerance. The bottom part consists of the hardware (PWB, semiconductors and a battery). The calculated ITVs of certain applications such as video gaming and battery charging are also listed in Table 3.6. Under these conditions, the temperature is within the target (44 °C), and the module designs can begin to satisfy the ITVs.

Table 3.6 Initial design parameters and ITVs in the development stage

Software	F	0.9 GHz
	St_{chg}	On
	St_{per}	On
Electrical Parts	C_l	0.4 μF
	V	2 V
	P_{chg}	0.4 W
	P_{per}	0.9 W
Mechanical Structures	l, w, t_1, t_2	120, 60, 5, 5 (mm)
	C_{ht}	11 W/(°C·m^2)
	λ_1, λ_2	0.1, 2 W/(°C·m)
Environment	T_{amb}	25 °C
ITVs	F	0.9 GHz
	St_{chg}	On
	St_{per}	On
	Q_p, Q_{chg}, Q_{per}	1.44, 0.4, 0.9 (W)
	T_{s_1}, T_{s_2}	34.6, 43.1 (°C)

The thermal risk of a new software application is studied during maintenance planning. As shown in Table 3.7 the new application requires a higher processor frequency to execute more tasks; consequently, the F rises from 0.9 GHz to 1.2 GHz. Because extra power is consumed by the processor, the surface temperature exceeds 44 °C. Referring to the temperature curve in Figure 3.2, the raised temperature will burn the user after 98 min of contact. Because the allowable time is considered as insufficient for the usage, temperature rise must be suppressed.

To reduce the thermal risk in a new application of updated OS, two alternatives are prepared as countermeasures. Alternative 1 is a software improvement that reduces the processor frequency of the application by optimizing the task scheduling in the software. Alternative 2 is a disable function that can be deployed at the same time. The tasks to be considered are executing an application and charging a battery. By disabling the charging, the power consumption of the voltage conversion loss is reduced.

Effect of these two countermeasure alternatives can be investigated using MDM. Using a MDM, relationships between thermal behaviors and structure can be described about each alternative. Comparing the relationships promotes understanding how the changes affect the product quality. The MDM shown in Figure 3.9 described the relationships of the system elements defined in the development. Based on the MDM, effects of countermeasure alternative 1 that changes processor's operating frequency are described in Figure 3.19. Change of the processor states affect power consumption of the processor, and heat transfer from the processor to the PWB. The operation at the lower frequency reduces generated heat of the processor. Although the improvement by optimizing the task scheduling in the software is required, the reduction of heat suppresses temperature rise of the product. Another countermeasure alternative 2 is described in Figure 3.20. Change of power supply state affects heat generation of the power supply. The heat transfer from the power supply is also affected disabling charging. Because the paths of the heat transfer lead to the surface from the electrical parts on PWB, temperature rise on the product surface is suppressed.

Table 3.7 lists the ITVs proposed in each countermeasure. If the calculated temperature exceeds the target, the thermal risk is evaluated from the probability and duration of usage. When the general usage time of the new application exceeds 98 min, the temperature rise should be mitigated even when no post-distribution hardware solution is available. Otherwise, the application should be discontinued at the point of product safety. However, although both countermeasure alternatives reduce the product temperature, alternative 1 does not reduce the temperature within the target. Nonetheless, provided that the application is rarely used for longer than 204 min, this countermeasure will largely reduce the thermal risk. While alternative 1 requires a software improvement effort and incurs risk during prolonged usage, alternative 2 is inconvenient for users. In particular, it may drain the battery power, disabling all features of the product. In the simulation based on the system model, the author can propose to evaluate a number of alternatives and select the most practical solution at different points. .

Table 3.7 ITVs developed in the support stage

		New App.	Improved	
			Alternative 1	**Alternative 2**
Countermeasure		-	Execute at a lower frequency	Disable charging
ITV	F	1200 MHz	1100 MHz	1200 MHz
	St_{chg}	On	On	Off
	St_{per}	On	On	On
	Q	3.22 W	3.06 W	2.82 W
	T_{s_1}, T_{s_2}	36.3, 46.3 (°C)	35.7, 45.2 (°C)	34.8, 43.6 (°C)
Allowable usage time		98 min	204 min	>480 min

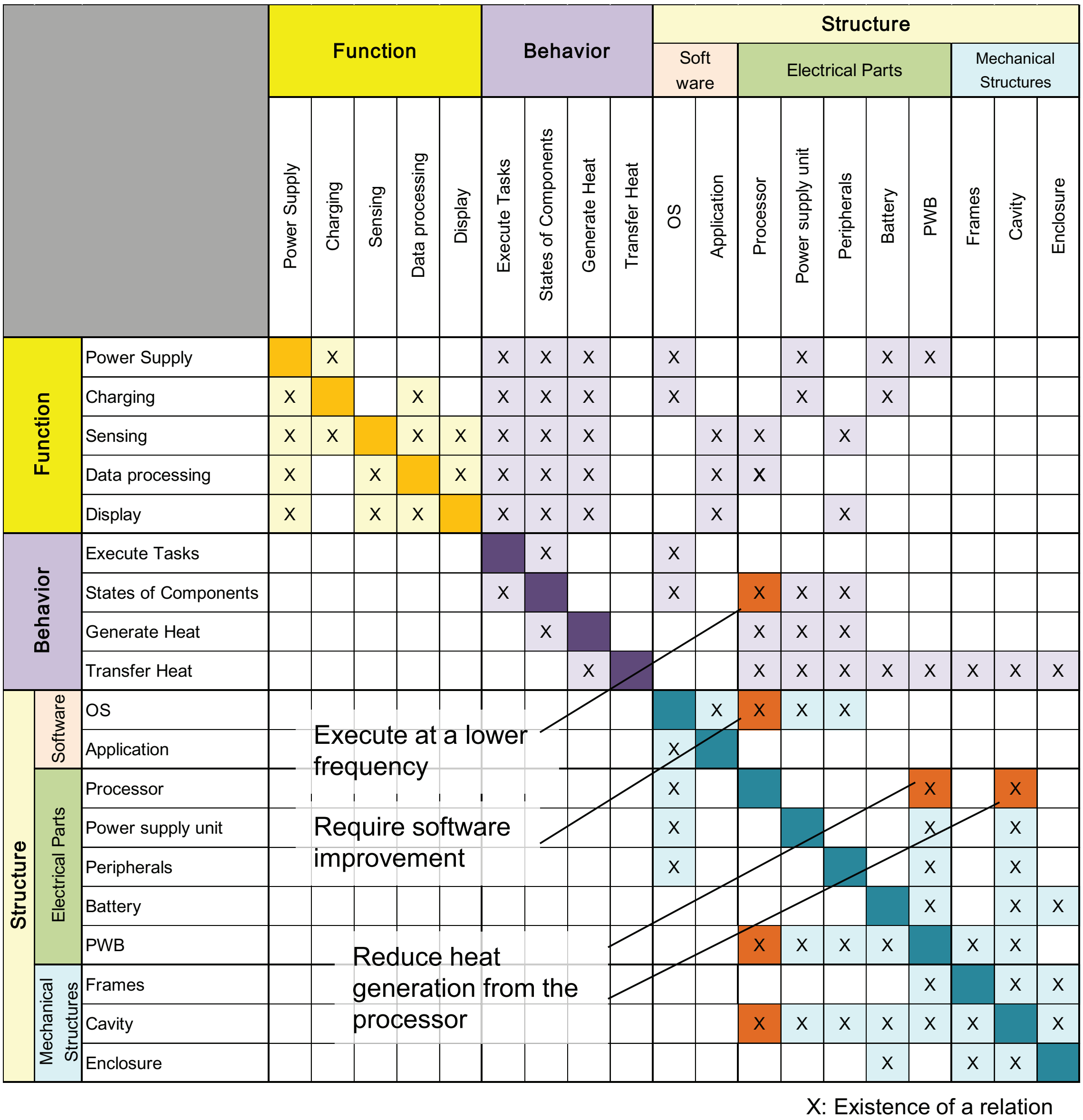


Figure 3.19 Relations of system elements of a smartphone described in case that operating frequency is changed (countermeasure alternative 1)

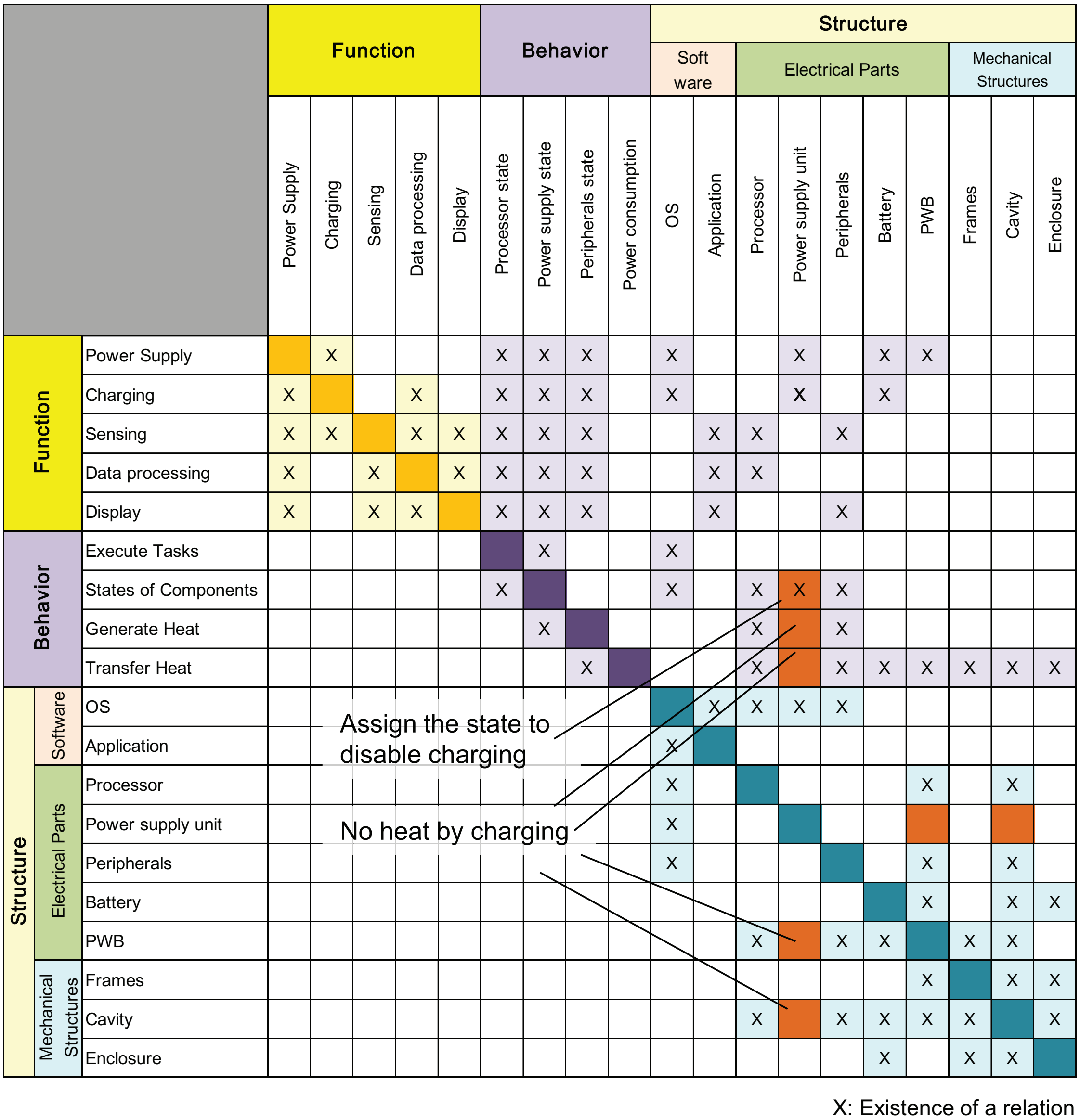


Figure 3.20 Relations of system elements of a smartphone described in case that charging states is disabled (countermeasure alternative 2)

3.6 Summary

This chapter described thermal design specification of a portable electronic product. The thermal system was decomposed to describe the thermal behaviors. Based on equations of heat generation and heat transfer, thermal simulation was performed referring occurrence condition of low-temperature injuries.

The above proposed approach was applied to smartphone thermal design. First application was parameter exploration for thermal design specification. This study introduced a thermal design approach for designing electronics products while considering user requirements. Using the simulation based on the system model, ITVs were calculated as boundary conditions among module designs, where the modules comprise the software, electrical parts, and mechanical structures. The author quantified the relationship between two conflicting user requirements, small size and long usage time, by evaluating thermal burn injury risk.

Then the author applied the thermal simulation based on the system model to prevent degradation of thermal quality due to design changes in the development. The countermeasure alternatives were generated by recalculation of ITVs. Changing each module design, the most practical solution can be identified. The design changes can be discussed among concerned parties to weigh the design parameters against requirements. Once the balanced ITVs are assigned to each module design, module design is being performed to satisfy ITVs. The benefits include reduction in the number of redesign iterations required to complete product development.

The author also applied the thermal design approach using the system model to prepare software changes in the support stage. Thermal simulations reflecting expected the states of the electrical parts were performed to generate countermeasures alternatives against further temperature rise. In the application, the author also investigated a verification workflow. By estimating this risk in advance, the author can limit the number of measurements in the verification. The thermal design approach using the system model provides an efficient verification, particularly when software changes in the support stage induce numerous and diverse product variations.

Chapter 4

Application to a Production System Considering Variability of Component Characteristics

4.1 Introduction

In this chapter, the author proposes an application of the system model to the production of portable electronic products. The thermal design of electronic products has become increasingly complicated due to the leakage current characteristics of semiconductors and their variability. After thermal design specifications are developed corresponding to the demands for faster processing speeds and smaller size, further heat generation occurs by the leakage current effect at production.

Because variability in the current characteristics is difficult to predict during the time of development, the leakage current effect hinders the product thermal design. Leakage current depends on temperature and increases more at higher temperatures during operation. In addition, the leakage current of a semiconductor processor increases with the trend toward miniaturization of the semiconductors components. Unexpected heat generation may cause low-temperature injuries during the utilization stage.

In the previous chapter, the author proposed to apply thermal simulation based on a system model to prevent degradation of thermal quality due to software changes in consumer electronics products; however, production problems, such as decrease in the yield ratio due to variability in component characteristics, were not considered. To estimate how thermal risk is affected by variability in the leakage current of a semiconductor processor during the production stage, in this study, the author proposes to reuse thermal simulations based on the system model used in architecture design. As described in Chapter 2, the system model of a consumer electronic product is developed to analyze its thermal quality. The system model is described using SysML to clarify interdependency among system modules in thermal design view.

In this chapter, the author reuses the system model of a portable electronic product, which includes a semiconductor processor, to describe its leakage effect characteristics. Then, the thermal behaviors of the system are simulated, considering variability in the leakage current characteristics of the semiconductor processor. In this chapter, portable consumer electronics products such as smartphones or tablets are assumed as examples.

Referring the thermal simulation results to the conditions of possible low-temperature burn injuries, the allowable range of component variability that satisfies a product's thermal quality requirements is calculated before it is put into production. During the early stages of the production, such as component inspection, the degradation of the product's thermal quality can be prevented by screening samples within the calculated range and installing the acceptable components. Moreover, the author proposes to apply thermal simulation to product variants. It is assumed that the same semiconductor processor is installed in products of the variant group. Thermal simulations are performed to determine the allowable range of variability in a semiconductor processor's leakage current characteristics for each product. Within this range, the processers are sorted to match the thermal characteristics of each product. Using these processor samples causes a stronger leakage effect in a product with sufficient heat spreading ability; thus, degradation of product quality can be prevented without losing the component yield ratio.

4.2 Thermal simulation model of leakage current effect

In this subsection, the author develops a system model describing interactions among the module parameters, so as to consider the leakage current effect of a semiconductor processor. Figure 4.1 shows the composition of the elements of the thermal system to analyze thermal quality during the production stage. The system model that was developed for architecture design is reused. In comparison with the model shown in Figure 2.5 in the development stage, the task execution activity is not emphasized because the states of electrical parts are kept static to verify the leakage current characteristics, upon which heat generation and transfer depend. This chapter describes the interaction between heat generation and transfer.

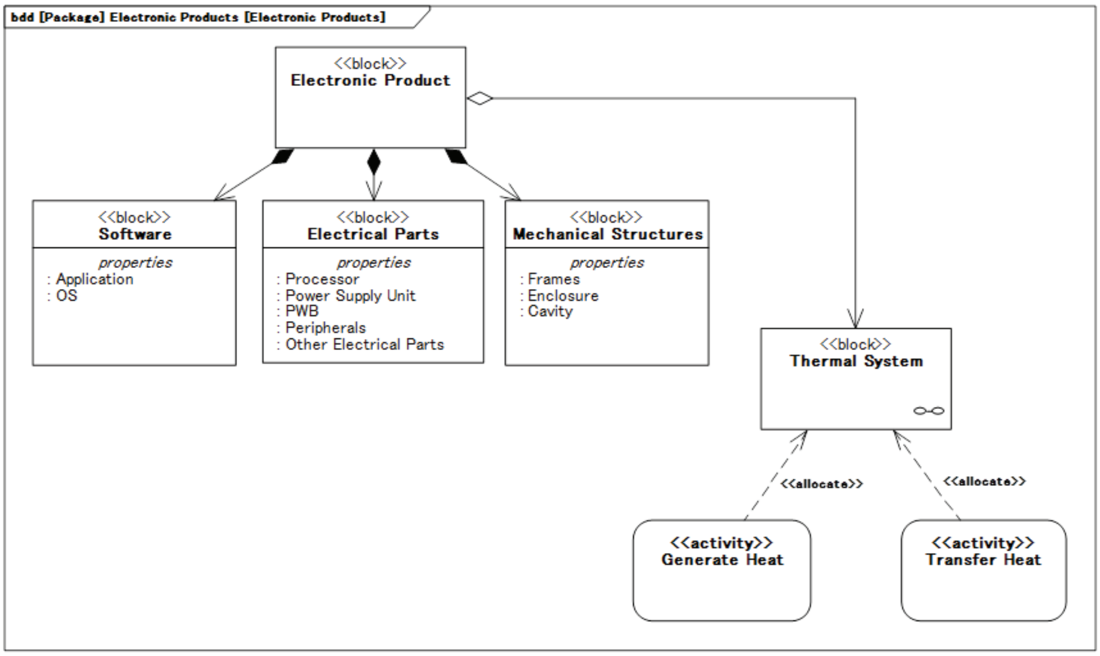


Figure 4.1 Composition of thermal system elements for analyzing product thermal quality in the production stage

The activity diagram in Figure 4.2 shows the thermal behaviors that cause a product's temperature to rise. The activities here are related to heat generation and transfer. During the operation of a product for a certain use case, tasks are scheduled according to an algorithm written in a kernel of an OS; the operating frequency and voltage at which data are processed are assigned to a semiconductor processor. Other states are assigned to peripherals, such as a display. Power supplied to the peripherals is also executed according to OS commands.

In a semiconductor processor, the power consumed in processing data is dissipated as heat; in other words, heat is generated by data processing (a-1). To supply power to a semiconductor processor and its peripherals, the power-supply unit controls power to prevent wasteful consumption and extend battery life during portable usage. Power loss by voltage conversion and electrical resistance is dissipated as heat during activity of the power supply (a1-2). The peripherals, including driver ICs, are operated according to OS commands and their consumed power is dissipated as heat (a1-3).

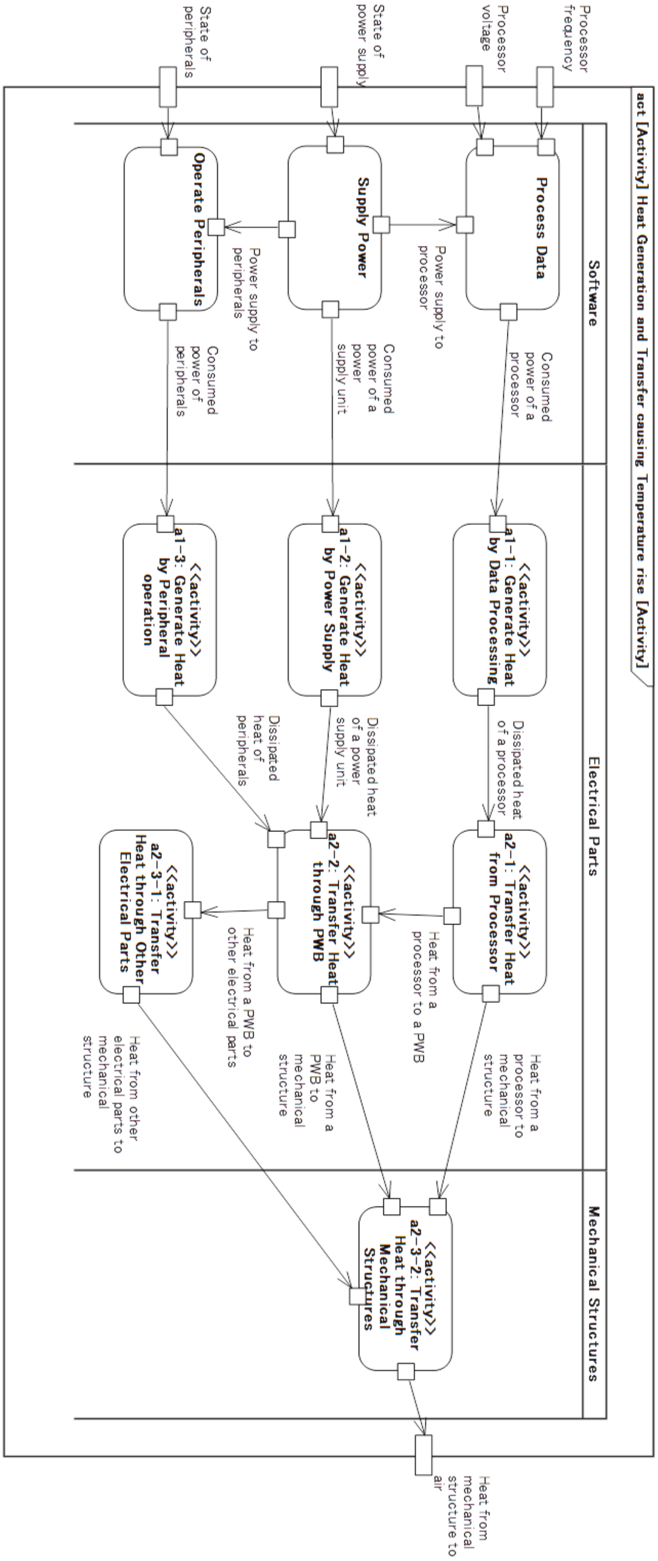


Figure 4.2 Activity diagram of heat generation and transfer causing temperature rise considering heat transfer through other electrical parts

Concerning heat transfer activities, heat generated in a semiconductor processor is transferred to the PWB through a soldering layer and dissipated from the surface of the processor into the air in the product's cavity (a2-1). Besides heat from the semiconductor processor, heat from the power supply and peripherals is also transferred and spread through the PWB (a2-2). Although, in this dissertation, the heat transferred through the PWB is considered to be the total amount of heat generated by the product, this is a simplification that neglects heat transfer through other electrical components that are not mounted on the PWB and mechanical structures.

The heat from other electrical parts is transferred from the PWB to mechanical structures (a2-3-1), and that from mechanical structures is transferred from the PWB and other electrical parts to the surrounding air (a2-3-2). Because other electrical parts and mechanical structures belong to different modules, the activities of each module are clarified using a SysML activity diagram. This diagram is expected to help clarify thermal behaviors and manage design parameters efficiently, especially if interactions among modules cause complexity in product development.

The block definition diagram in Figure 4.3 shows the above-mentioned activities that are allocated by the thermal system and associated with constraints. The six constraint blocks contain equations for describing these activities. The above three constraints include heat generation equations for a semiconductor processor, a power supply, and peripherals. Other three constraints include heat transfer among modules and temperature rises of the semiconductor processor and the surface.

The author presents the heat generation equation for a semiconductor processor, considering leakage current effects in the constraint block of the processor heat generation equation in the diagram shown in Figure 4.3. As shown in Eq. (4.1), the heat dissipated from a semiconductor processor Q_p is the sum of the dynamic power for data processing (1st term) and the static power (leakage power), which increases with the leakage current effect (2nd term):

$$Q_p = F \cdot C_l \cdot V_{dd}^2 + I_{ls} \cdot V_{dd} \tag{4.1}$$

The dynamic power varies with the operating frequency F and voltage V_{dd} of a semiconductor processor. Here, the capacitance of the semiconductor processor is C_l and this processor is assumed to be fully activated.

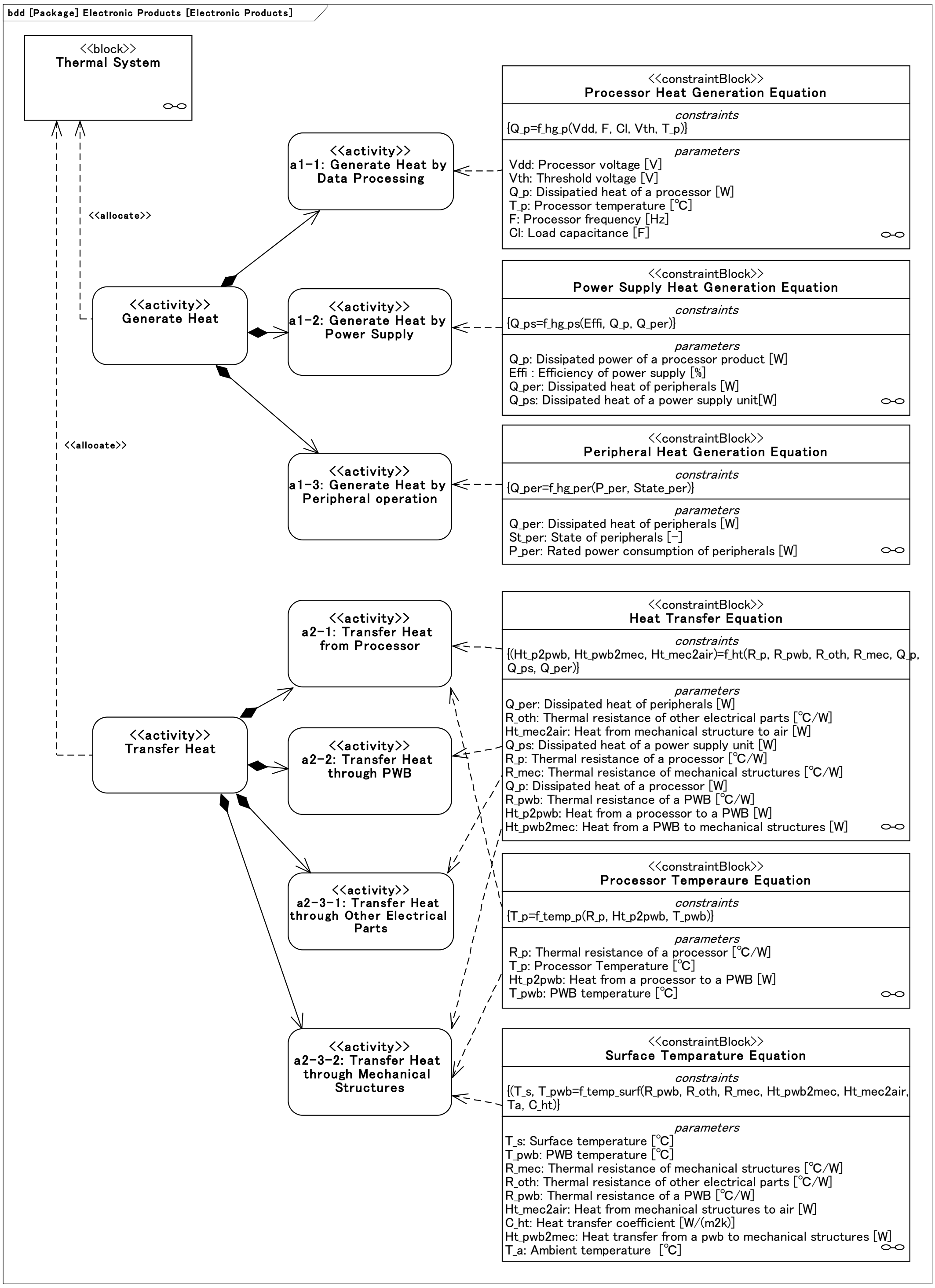


Figure 4.3 Activity and constraint relations considering the leakage current effect

There are three leakage currents to consider, including subthreshold leakage current, gate leakage current, and source/drain leakage current. In general, subthreshold leakage current occurs more than the other two leakage currents. As early as in 2005, it was reported that subthreshold leakage current accounted for 79% of the entire leakage current in a benchmark circuit (Chang and Sapatnekar, 2005). The process node of the transistor model for the fabrication was 100-nm wide; because of a more refined fabrication process for semiconductors, the percentage of leakage current that can be accounted for by subthreshold effects has increased.

However, gate leakage current has also increased with refinement of semiconductor fabrication, and does not depend on temperature. In recent years, high-dielectric-constant materials (high-k) have been introduced to help suppress gate leakage current. Source/drain leakage current is not affected much by the refinement of semiconductor fabrication or temperature rise; therefore, this dissertation considers only subthreshold leakage current. Subthreshold leakage current I_{ls}, described in Eq. (4.2), varies exponentially with the variability in threshold voltage V_{th} and the temperature dependency of temperature voltage U_t.

$$I_{ls} \propto \exp((-V_{th}) / (n \cdot U_t)) \tag{4.2}$$

Here, n is the subthreshold coefficient, with a typical value of around 1.3–1.5 (Matsuzawa 2014). As described in Eq. (4.3), temperature voltage Ut is proportional to the absolute temperature of a semiconductor processor, T_p:

$$U_T = (k \cdot T_p) / q \tag{4.3}$$

Here, Boltzmann's constant k is 1.38 x 10^{-23} eV/K, and the electric charge q is 1.60 x 10^{-19} e; K is the unit of absolute temperature.

In Figure 4.3, the temperature of the semiconductor processor, T_p, is in two constraint blocks, the processor heat generation equation and the processor temperature equation, and depends on heat generation and transfer. T_p is in the constraint property of heat transfer and is clearly used as the parameter in the constraint property of heat generation. In other words, there is an interactive relationship between heat generation induced by leakage power and heat transfer. If heat transfer within an electronic product is insufficient to decrease processor temperature due to large thermal resistance, a vicious cycle is formed. Higher processor temperatures induce higher leakage power.

The parametric diagram in Figure 4.4 shows the relations among the design parameters used in the thermal simulation. In the figure, the three constraint properties on the left-hand side represent the heat generation equations and those on the right-hand side represent heat transfer. Parameters of the constant properties are also shown in Figure 4.4. At each heat transfer path that dissipates heat from a semiconductor processor to the surface, the transferred heat value is calculated with three dissipated heat parameters: Q_p, Q_{ps}, and Q_{per}. After the dissipated heats are calculated using the constraint properties of heat generation, heat transfer among the modules is calculated. Then, the temperatures of the semiconductor processor (T_p) and product surface (T_s) are calculated with the transferred heat values. Surface temperature T_s depends on the heat transferred from product surfaces to the surrounding air and on heat transfer coefficients.

On the other hand, the temperatures of components located inside of the product, such as the processor temperature T_p, depend on thermal resistance at each heat transfer path, transferred heat value, and adjacent component temperature. T_p is used in the calculation of heat generation with the processor heat generation equation on the left of the figure. Using the parametric diagram, the interdependency between the parameters of heat generation and heat transfer is clearly expressed. Thermal resistance is a parameter of heat transfer within objects that include mechanical structures and PWB. The unit of thermal resistance is °C /W, and the value of thermal resistance due to the conductivity of an object can be calculated with the thermal conductivity that depends on material properties, the cross-sectional area of the heat transfer path, and dimensions such as object length.

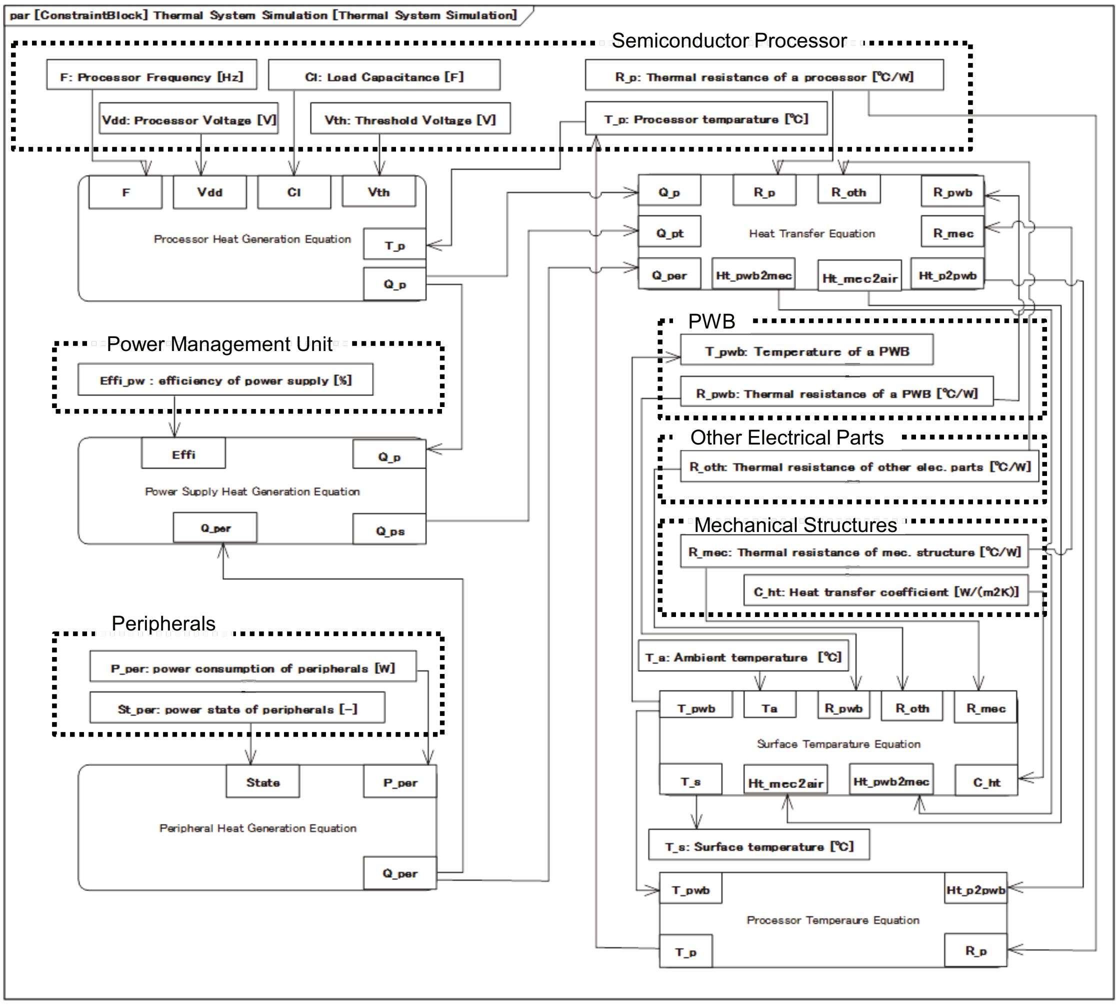


Figure 4.4 Parametric diagram of the temperature constraint considering the leakage current effect

To calculate the transferred heat and temperature in thermal simulations, thermal network analysis is often used as mentioned above. To improve the accuracy of the calculation, it is effective to model the heat transfer characteristics of highly detailed mechanical and electrical parts and to employ a calculation using CFD that covers radiation and convection (Seki et al. 2008). If the verification of a simulation model referring the measurement result of a prototype is available, updating the parameters used in the simulation, such as thermal resistance, will improve the simulation accuracy. For thermal simulation in this chapter, CFD is applied.

In this dissertation, surface temperature T_s is simulated to estimate the risk of low-temperature burn injuries by a portable electronic product. The parametric diagram clearly shows which parameters affect T_s. In addition to the design parameters of electrical parts, such as the dynamic and static power of a semiconductor processor, the efficiency of the power supply, and the dissipated heat of the peripherals, T_s. is also affected by the thermal resistances of mechanical structures and electrical parts, as well as the ambient temperature. Visualization of the interaction effects helps to accelerate exploration of design parameters among disciplines. To design the derived products in the same product variants, their product characteristics can be simulated by changing the key design parameters of modules. For example, the operating frequency F is increased to accelerate the speed of data processing. The thermal resistance of mechanical structures, R_{mec}, is increased to simulate the case in which the outer dimensions of mechanical structures, including the enclosure and cavity, are expanded because of the installation of a larger display.

4.3 Thermal management considering variability in semiconductor characteristics

First, this section describes the cases in which simulation based on the system model is performed during product development. The V-model (Forsberg at al. 2005) in Figure 4.5 shows the product development workflow. The vertical V-shape with a broad width represents the decomposition and integration of a product. The horizontal V-shape represents the processes of determination of system requirements, definition of system specifications, manufacturing or coding, verification, and validation in the respective levels of the system, subsystem, and component.

Electronic products consist of modules such as software, electrical parts, and mechanical structures. Because the modules are technologically based on different disciplines, the design of an electronic product has to consider interaction of modules and various design constraints. Therefore, it is important to undertake design with consideration of the entire system in the early stages of development shown on the top left of the V-model, in order to prevent unintended fatal iterations of the design work.

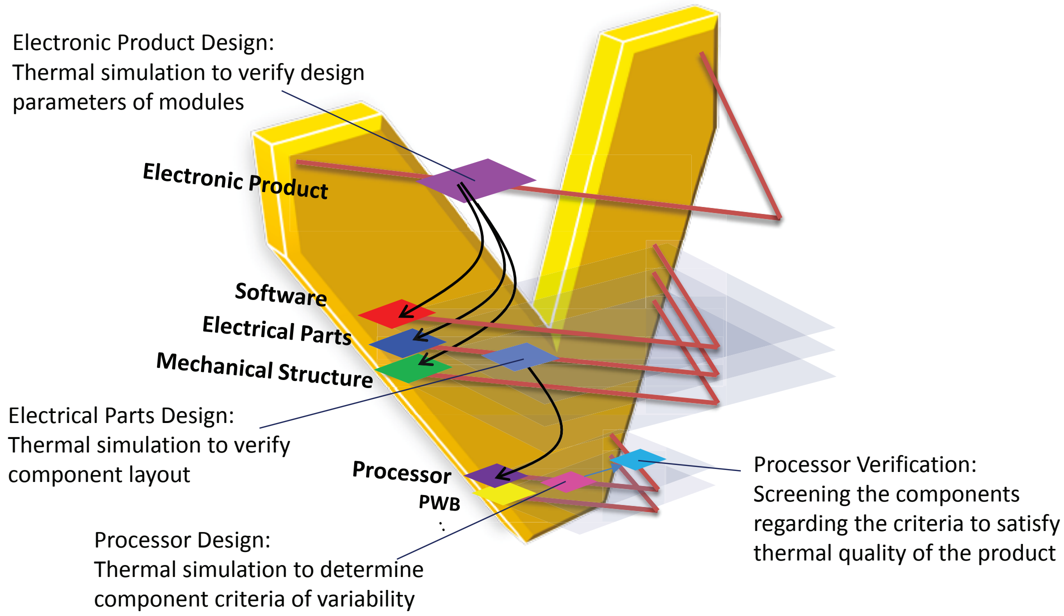


Figure 4.5 Product development workflow

Simulations based on the system model, which describes interactions among modules, are employed to verify that module design specifications meet the system requirements for a product. Thermal simulation is a typical means of performing this verification. In the electrical component design shown in the middle left of the V-model in Figure 4.5, the layout of parts on the PWB is designed to not only simplify the writing pattern but also to maintain a certain distance between the electrical parts that generate heat, so as to spread heat throughout the PWB. For such a PWB design, thermal simulation is used to calculate the temperature distribution with models of the electrical parts (Seki et al. 2008).

To satisfy product thermal quality, the author proposes to determine the allowable range of variability in component characteristics at the prototyping phase before mass production of the product. Because portable electronic products must be made ever smaller and lighter, variability in threshold voltage, which is increased by miniaturization of the semiconductor fabrication process, seriously affects the product's thermal quality. In the case where the variability is found in the early stages of production, such as component unit testing during acceptance inspection, it is difficult to estimate the thermal quality of the product while disregarding heat transfer in the product's whole structure and interactions between heat transfer and generation.

In this dissertation, the author proposes to employ a thermal simulation model that describes interactions among the design parameters of the modules to determine the allowable range of variability in a semiconductor processor's threshold voltage. The thermal simulation model can be reused after it is employed to define the architecture during the early phases of product development. Referring to the determined range as criteria, semiconductor processor samples are screened during the verification of prototypes shown at the bottom right of the V-model in Figure 4.5. Comparing the simulation results with the measured characteristics of the product using prototypes, the simulation model is verified. Then, examination of the quality of the components in the process of mass production is enabled.

If the variability in the component characteristics is larger than expected in mass production without screening, unacceptable components can be integrated into modules. After the modules are integrated into products, the product qualities of a large number of samples become degraded. Therefore, screening and removing such components before integration prevents the degradation of the product. Even if the unacceptable components are integrated and the product sample fails a quality test after assembly, costs of repair or disposal of the product are incurred. This oversight may also lead to a higher risk of low-temperature burn injuries during utilization of the product samples leaked to the market. With determination of the acceptable range of component characteristics using thermal simulation, screening components during the production process serve to prevent glitches.

4.4 Application to themal design in the production stage

4.4.1 Effect of variability in leakage current

First, the author describes the effect of variability in component characteristics, such as the leakage current of a semiconductor processor. The leakage current has increased with the trend toward miniaturization of the semiconductor's fabrication process, as mentioned above. Moreover, the temperature rise induced by leakage current is sensitive to variability. This variability in component characteristics is a factor leading to yield and product quality degradation (Saeki at al. 2009).

To determine the effect of variability in threshold voltage on leakage current, the value of threshold voltage in Eq. (4.2) is varied in the simulation model. Figure 4.6 shows examples of the probability density distribution of V_{th}. and Figure 4.7 simulation results of the relation between processor temperature and leakage power with three threshold voltages: 0.32 V, 0.34 V, and 0.36 V. As Figure 4.7 shown, leakage power increases with processor temperature. Leakage power increased by 7.9 times under processor temperature rise from 20 °C to 100 °C in the case where V_{th} is 0.34 V. In addition, if V_{th} changes from 0.34 V to 0.32 V, the leakage power increases by 64% at 60 °C. Therefore, the increase in leakage power with processor temperature is difficult to ignore in the power performance of a semiconductor processor. In the case where the dynamic power is 2 W and the processing temperature is 60 °C, leakage power accounts for 15% of the total power of a semiconductor processor.

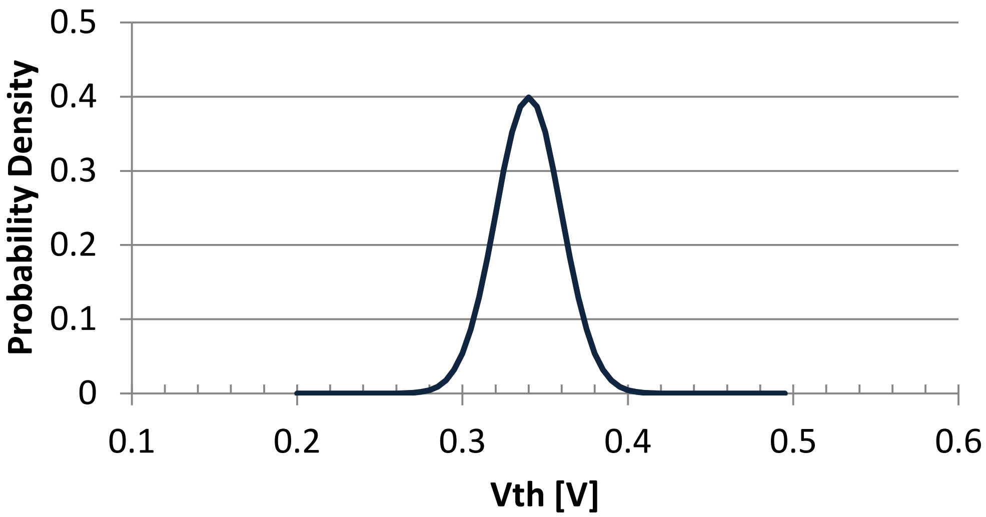


Figure 4.6 Variability in threshold voltage

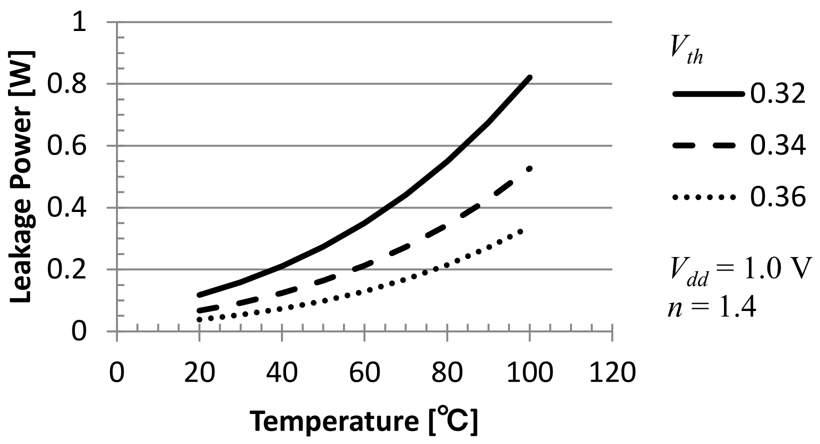


Figure 4.7 Temperature and leakage power relations

4.4.2 Prevention of thermal quality degradation by screening semiconductor processor samples

In this subsection, the surface temperature T_s of a general portable electronic product is simulated under varying threshold voltage V_{th}. Comparing the simulation results to the conditions of low-temperature burn injuries, the allowable range of variability in threshold voltage V_{th} is determined so as to satisfy product thermal quality.

Figure 4.8 shows the thermal simulation result of surface temperature T_s when V_{th} is allowed to vary as shown in Figure 4.6. The electrical parts and mechanical structures are simplified and located within an enclosure whose outer dimensions are 124 × 64 × 10 mm^3. When ambient temperature is 25 °C and threshold voltage V_{th} is the mean of the distribution, 0.34 V, peak surface temperature T_s is 42.3 °C. It is believed that product surface temperatures of 43 °C or less do not cause low-temperature burn injuries; therefore, the mean threshold voltage V_{th} satisfies the product thermal quality constraints. However, V_{th} has a large variability, so surface temperature T_s also varies significantly. If V_{th} is 0.32 V or less, surface temperature T_s exceeds to 43 °C. Product thermal quality is unacceptable in that case because of the possibility of low-temperature burn injuries.

By estimating the effect of component characteristic variability upon a product's thermal quality, the allowable range of this variability can be determined before mass production. After screening the components, only those that satisfy the quality constraints can be integrated, thus ensuring product safety.

To realize this control, processes for acquiring individual component sample characteristics and sorting samples based on simulation results are required before components can be implemented. Such data can be acquired from the results of electrical characteristic testing during a post process of semiconductor fabrication, or measured during the receiving inspection process using test sockets that enable insertion and removal of components.

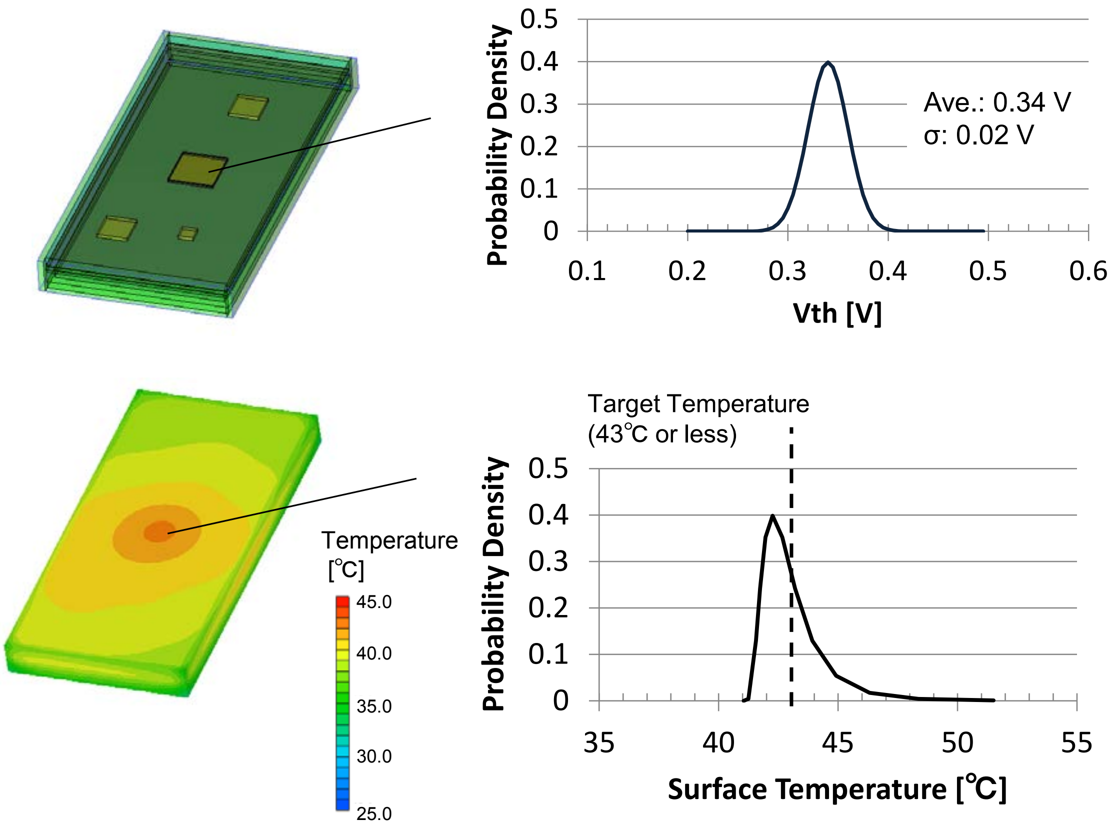


Figure 4.8 Variability in surface temperature

4.4.3 Sorting processes for matching thermal characteristics in product variants

To reduce the component waste that may be caused by the above-mentioned screening, this dissertation proposes efficient implementation of the components of product variants. It is assumed that the same type of semiconductor processor that is incorporated into a product is also incorporated in its variants. Table 4.1 shows three variant products considered in this subsection. Although the same models of semiconductor processors are installed in all three products, the outer dimensions and conditions of processor operation differ. Design parameter changes for each product characteristic in each variant are simulated numerically. Product A is the product shown in Figure 4.8; a relatively fast semiconductor processor is implemented in small size.

Product B is assumed to be a high-end model of larger size; although the conditions of processor operation are the same as those of Product A, additional peripherals are implemented for Product B. Therefore, heat dissipation by Product B is increased over that of Product A because of the additional power consumed by the peripherals. On the other hand, heat transfer due to natural convection is promoted in Product B because of its larger surface area and larger outer dimensions. Because larger mechanical structures increase the thermal resistances of mechanical structures, R_{mec}, and increase in heat dissipation by the peripherals, Q_{per}, promotes temperature rise, quantitative evaluations, such as thermal simulations, are necessary to estimate temperature rise. Product C is the low-end version of Product A; the speed of data processing is suppressed due to limitation of the maximum operating frequency F, so the heat dissipated by the semiconductor processor Q_p is smaller than those of the other two products.

For each of these three products, the allowable range of variability of the same semiconductor processor is determined to satisfy product thermal quality, using thermal simulations. Figure 4.9 shows the variability in the peak surface temperatures of Products A, B, and C according to the variability in the threshold voltage, V_{th} of a semiconductor processor. The target temperature on the product surface is set to 43 °C or less to prevent low-temperature burn injuries; thus, the threshold voltage of a semiconductor processor incorporated into Product A must be 0.32 V or higher. If semiconductor processors are screened based on the limitations for Product A, 73.4% of all units will be passed. This means that 26.6% of the units are not passed and are judged unfit for integration.

For Product B, the threshold voltage of an implemented semiconductor processor must be 0.29 V or higher to satisfy the product thermal quality, and 98.3% of all units are passed. Therefore, most of the unacceptable samples for Product A can be implemented into Product B. The remaining 1.7% of the samples can be implemented into Product C, which has a wider allowable range of variability. The threshold voltage of a semiconductor processor that is implemented into Product C must be 0.27 V or higher to satisfy the product thermal quality constraints, and 99.9% of all units pass this threshold.

Thus, high risk component samples of relatively low V_{th} can be implemented in products with wider allowable ranges of component characteristic variability. Sharing the data concerning the characteristics of individual component and sorting units allows realization of matching thermal characteristics for product variants, so as to maintain product thermal quality and efficient implementation of these components.

Table 4.1 Differences among the three products

	A	B	C
Dimensions [mm]	124 × 64 × 10	144 × 7 × 10	124 × 64 × 10
Semiconductor processor Frequency [GHz]	2	2	1.2
Power Consumption of Peripherals [W]	0.5	1	0.5

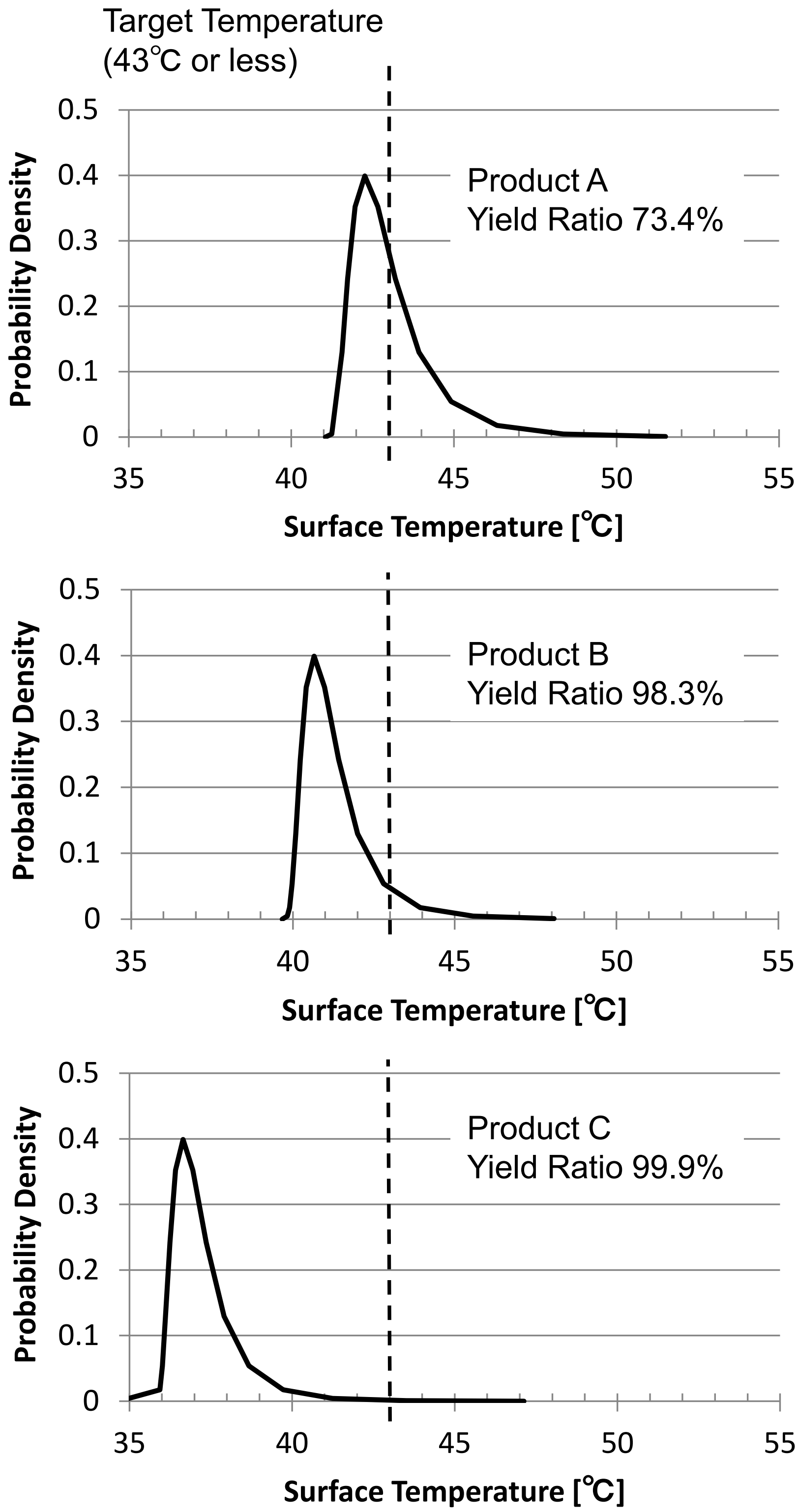


Figure 4.9 Component sorting for various products

4.5 Summary

This dissertation proposed simulation based on the system modeling conducted during early phases of production (such as receiving inspection) with consideration of variability in a semiconductor processor's leakage current effect, so as to satisfy product thermal quality constraints. The system model developed in the early stage of product development to define architecture was reused. The model was described with SysML considering interactions among parameters of mechanical structures and electrical parts including semiconductors with temperature-dependent leakage current characteristics.

To satisfy product thermal quality, the author proposed determining the allowable characteristic variability ranges of components during the prototyping phase before mass production. In this chapter, product surface temperature was estimated based on the variability in the leakage current of a semiconductor processor using thermal simulation of a portable electronic product. By comparing these results to the condition at which low-temperature burn injuries are possible, the allowable variability range of the component was calculated prior to mass production of the product. Screening components to meet the allowable range of variability enabled satisfaction of thermal quality constraints.

In addition, the system model was applied to describe product variants that use the same semiconductor processor but change the parameters in the thermal design view. Employing simulations based on the system model, the allowable range of component variability was determined for each product. Sorting semiconductor processor samples and matching thermal characteristics in product variants enabled maintenance of the product's thermal quality and efficient implementation of the components.

Chapter 5

Conclusion and Future work

5.1 Conclusion

This dissertation illustrated a thermal design method for portable electronic products using system modeling. The purpose of this research was to satisfy thermal quality constraints through the product lifecycle and prevent fatal iterative work. Both heat generation and transfer behaviors were modeled. The portable electronic product included software modules, electrical parts, and mechanical structures, and the thermal behaviors related to the basic functions and structure were described in the thermal design view. The author developed a thermal simulation model based on the system model, coupling design parameters and constraints among different disciplines. As a design constraint to satisfy product thermal quality, temperatures resulting in low-temperature burn injuries were quantified. Architectural candidates were assessed using thermal simulation based system model, considering the design constraints. This approach enabled more efficient and comprehensive evaluation of the quality of portable electronic products during the product development stage.

To prevent fatal iterative work, this dissertation proposed defining and managing target values for module designs in the thermal design view. The target values named ITVs would be the boundary conditions of module designs for managing factors that affect thermal quality. These included the states of electrical parts controlled by software, heat from electrical parts to mechanical structures, and the surface temperature of the product. During architectural design, ITVs would be determined through cooperation among module design groups and distributed to satisfy product quality.

In addition, visualizing relations among system elements in the thermal design view using MDM was proposed to promote a common understanding among module design groups. A portion of the DSM structure was arranged into a thermal coupling matrix (TCM) to visualize the thermal coupling condition. The descriptions of architectural candidates using MDM and their comparison in terms of ITVs were demonstrated. The author also described the proposed thermal design process expressed in DSM. Through product development, ITVs are expected to be updated to adapt to design changes. This work of updating ITVs would prevent fatal iterative work at the time of integration, which may occur during the late stages of development.

This dissertation also described the thermal design specification of a portable electronic product. System modeling was applied to smartphone thermal design. The thermal system was decomposed to describe its behaviors. Based on equations of heat generation and heat transfer, thermal simulation was performed referring to the condition of low-temperature burn injuries. The first application of this model was to explore the parameters for thermal design specification. This dissertation introduced a thermal design approach for electronic products with consideration of user requirements. In the simulation based on the system model, ITVs were calculated as boundary conditions among module designs, which comprised software, electrical parts, and mechanical structures.

The next application was updating ITVs to prevent degradation of thermal quality due to design changes. Thermal design using system modeling could also be used to identify design changes that conform to product specifications. The candidates for improvement were developed by recalculation of the ITVs. The changes could be discussed among concerned parties to weigh the design parameters against conflicting requirements. Once affordable ITVs are assigned to each module design, the module design can be performed to satisfy these ITVs. The benefits may include preventing fatal iterative work required to complete product development.

In addition to the applications for product development, thermal design using system modeling was applied to estimating thermal quality and preparing measures in case of software changes during the support stage. In this application, the author presented a verification workflow. The simulation model suggested improvements that could be activated under increased thermal risk. By estimating this risk in advance, the author could limit the number of measurements needed for verification. This system-design approach will allow efficient verification, particularly when software changes in the support stage introduce numerous and diverse product variations.

This dissertation also applied the system model to the production stage of the product lifecycle. To prevent quality degradation with variability of component characteristics, such as the leakage current of a semiconductor processor, a simulation model was developed to consider interactions among the parameters of mechanical structures and electrical parts. Thermal simulation was employed to determine the allowable range of variability in the leakage current characteristics that satisfied a product’s thermal quality constraints. With this limitation, components that cause quality degradation can be screened using thermal simulation results before their implementation into finished products. In addition, using simulations that change the design parameters of a product to consider product variants with the same semiconductor processor, the allowable range of component variability was determined for each variant. Sorting semiconductor processor samples and matching thermal characteristics in variants enabled maintenance of product thermal quality and efficient implementation of components.

Shortcomings of this research included lack of quantitative consideration of other design constraints besides thermal quality, such as electromagnetic compatibility (EMC). Besides the disciplines of modeling and simulation, this research can be applied to a wide range of product lifecycles. The design approach using system modeling can be related to the need of stakeholders to resolve conflicts between requirements.

5.2 Future work

The author aims to apply the proposed thermal design method using system modeling to actual thermal design projects in an enterprise to assess its effectiveness. The author also aims to expand this design method to an earlier stage of concept design to consider further user requirements and to develop a design methodology of system architecture considering trade-off relations between thermal quality and conflicting user requirements, such as a processing speed. Changes in the user’s needs should also be considered under each use case.

Quantitative consideration of other design constrains besides thermal quality is another challenge for developing this design method. The author aims to apply system modeling to solving problems of thermal and EMC design. Considering design constrains in addition to thermal quality, this design approach using system modeling offers more advantages that contribute practically to product development.

In addition to the disciplines of modeling and simulation, this research can be developed for more detailed product lifecycle management. Design approaches using system modeling can be related to both stakeholder needs to resolve conflicts between requirements and to detailed design information throughout the lifecycles of product groups. According to the product lifecycle management methodology, the model and related information including requirements and verification results should be archived in the repository of an IT system. This enables traceability of product value, including product quality, to be maintained in the case of design changes. If enough information is available and maintained to model system elements in detail, virtual prototyping will become available to solve more issues efficiently in advance.

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