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A SYSTEM-LEVEL THERMAL DESIGN SPECIFICATION DEVELOPMENT OF ELECTRONIC PRODUCTS CONSIDERING SOFTWARE CHANGES

Yoshio MURAOKA, Kenichi SEKI, Hidekazu NISHIMURA
Keio University, Japan

ABSTRACT

Realizing the market demand for small size and fast processing speeds, thermal design is one of the major challenges in the development of electronic products. In addition, there are many software changes necessary to adapt to the rapid-moving trends in customer applications. Therefore it is difficult to develop a product design specification in the early stages of product development. In this study, we first introduce a typical system-level thermal design simulation method, coupling activities among modules related to software, electrical parts, and mechanical structure. In particular, this method allows us to evaluate risks related to thermal burn injury depending on the software's application. Then, we investigate this method by applying it to a design process case for electronic products that require software changes, such as having additional applications. The system-level simulation can be used to evaluate the thermal risk that may rise by the applications. We verify the design control to satisfy product quality using Systems Modeling Language (SysML) and the resulting design specification of the system architecture.

Keywords: thermal design, SysML, software change, electronic products, simulation, collaborative design, low-temperature burn injury

Contact:
Yoshio Muraoka
Keio University
Graduate School of System Design and Management
Yokohama
223-8526
Japan
yoshio@a2.keio.jp

1 INTRODUCTION

1.1 Thermal design of electronic products

In the development of electronic products, realizing a suitable thermal design has become increasingly difficult because of the demand for small size and fast processing speeds. Although technology for power reduction and heat spreading has continually been developed, product temperatures have become high, especially when handling contents-rich applications such as video games or shooting HD video (Consumer Reports, 2012, Qualcomm, 2012). Therefore, thermal design methods are fundamental technologies and implemented in different ways, depending on the business model and product features (Ulrich and Eppinger, 2007). Figure 1 shows an example of an electronic product that has several layers of modules. In the modules, the semiconductors within the electrical parts dissipate heat based on the software. Because mechanical structures spread heat, the objects targeting in thermal design include all the modules shown in the figure.

Each component of a product has a proper operating temperature range, and high temperatures may cause defects in a product. Moreover, high temperatures of the enclosure can cause low-temperature burn injuries when user touches a product. Even temperatures that do not appear high to a user and that are not too hot to touch may cause burn injuries when touched for prolonged periods. To prevent defects or burn injuries, thermal management must be properly designed for both hardware and software, such as power control (Jung, 2012). It is challenging to balance safe quality and performance to satisfy market demands for small and high-speed processing devices.

Because current electronic products are based on computer technology, the products can have multiple functions that run when switching applications. In other words, new product applications are implemented to satisfy customer requirements. If a given product allows a customer to install applications, it is possible to have additional applications even after product development has ended. For example, many electronic products such as phones, TVs, and music players, support the Android Operating System (OS), and many of them allow customers to install applications through a website named Google Play. In addition, manufactures develop and install in-house applications onto their products. Because the number of applications and application conditions are platform-specific, there is the need to change software when the OS is upgraded. By doing so, there is a greater possibility that verification procedures are not adequately covered from the perspective of performance and quality, which are related to low-temperature burn injuries. However, if software changes such as the addition of applications lead to degraded product quality, it should be properly resolved to improve the thermal design aspect of product development.

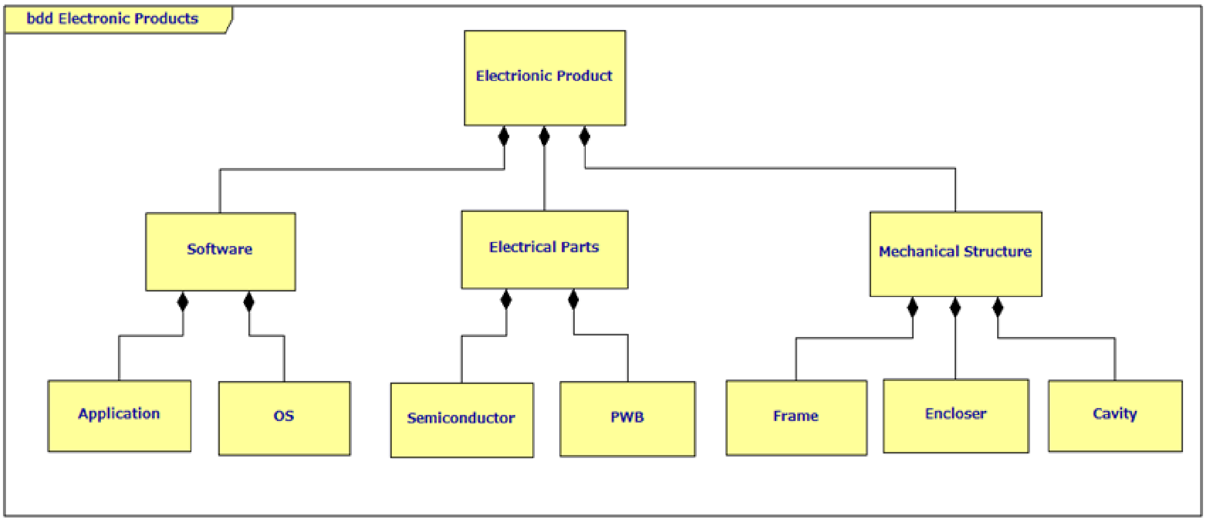

Figure 1. Example of modules of an electronics product

1.2 System-level design approach

For a collaborative design to prevent thermal problems such as low-temperature burn injuries, this study proposes a design approach using a system-level simulation to develop a product design specification. This approach is also called a Model-Driven Development method. In terms of concurrent design among multi-disciplinary design teams, Balmelli (2007) proposed the Model-driven systems development method using SysML. This approach uses multiple viewpoints, such as operational, functional, and physical views, to separately address different engineering concerns while maintaining an integrated representation of the underlying design. Goto and Eguchi et al. (2012) also proposed multilayer modeling of structure/behavior/requirements using SysML to describe product design information. They utilized the method to realize an impact analysis of the design change from the initial design. To manage structural and behavioral complexity, Diepold and Biedermann, et al. (2010) proposed combining structural and hybrid dynamical system models. Using matrix-based method, such as Domain Mapping Matrix (DMM), structural systems can be simplified, but cannot describe the behavior. The approach, that combines structural and mathematical modeling, results in a discrete-time dynamical representation of the system’s dynamics.

For the collaborative design of consumer electronic products, Seki and Nishimura, et al. (2011) investigated a module-based design approach using SysML. This study proposes the use of Initial Target Values (ITVs) as tentative boundary conditions to assign different sites for designs, and refines it during the design process. This approach contributes to the prevention of inconsistent performance of modules owing to a lack of communication between design sites and iteration of work required to correct such inconsistencies using ITVs during the independent module design. Seki and Nishimura (2011) also proposed a thermal design approach using Design Structure Matrix (DSM) and DMM to systematically assign ITVs. In this study, ITVs are created between module design pertaining to electrical parts and mechanical structures, particularly including cavities. Because software is not designed as modules, this study does not consider about change of applications of a product.

To adopt software changes related to product quality, this study investigates a thermal design approach that creates and assigns ITVs across module designs that include software at a system design phase. While the quantification of temperature causes low-temperature burn injuries, thermal risk is evaluated at system-level simulation. The risk evaluation at early stages of product development reduces the number of iterations required to redesign the thermal management specification during the development process. In this study, we investigate the thermal simulation model using SysML. Then, we apply the system-level thermal model into a simple case of product development using ITVs to discuss the benefits to product development.

2 SYSTEM-LEVEL THERMAL MODEL

2.1 Temperature rise of an electronics product

In this study, a simple model of an electronics product is described from the perspective of its temperature rise during given operation. Figure 2 shows the temperature rise of the electronic product. As shown in the figure, electrical parts such as semiconductors are on a printed-writing board (PWB) that is fixed to a mechanical structure. This figure also shows activities that cause the temperature rise. During operation of the product, semiconductors are being executed (a1). Because the consumed power is dissipated as heat, heat is considered to be generated by the operation within the semiconductors (a2). Then, the heat of the semiconductors is transmitted to the surface (a3). Figure 3 is a SysML activity diagram used to describe the temperature rise of electronic products. In the diagram, the flow of the actions is described by defining values that cause temperature rise and those that are transmitted between actions. During the operation, software executes operations in the semiconductor and the load is processed at a specific frequency (a1). Therefore, the heat generation can be described by assigning load frequency to a semiconductor (a2). The operation dissipates heat in the electronics parts and it is transferred to a mechanical structure (a3). The temperature rise of the product is the output of this process.

2.2 Thermal risk of low-temperature burn injuries

The temperature rise of electronic products causes different types of problems, such as parts failures, system defects, and burn injuries to the user. Because electronic products are becoming small and their capabilities are continuously increasing, the surface temperatures of many products increase during operation (Roy, 2012). Therefore, thermal design proposed in this study is aimed at preventing low-temperature burn injury. The temperature criteria are targeted by referring to previous studies.

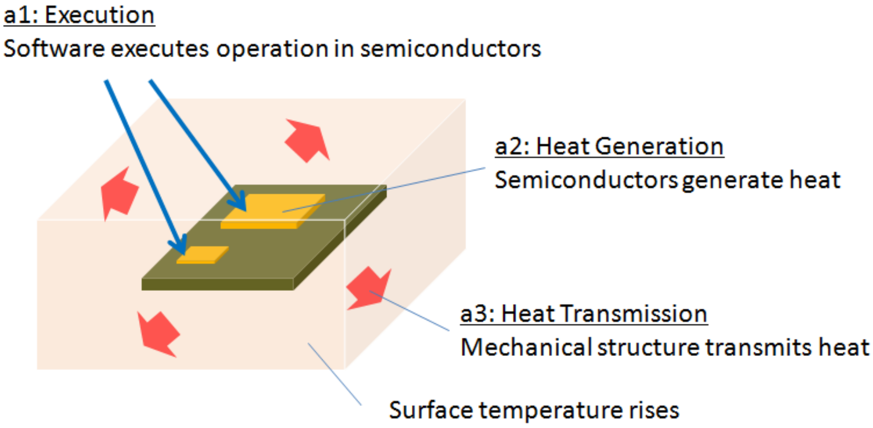

Figure 2. Temperature rise of electronic products

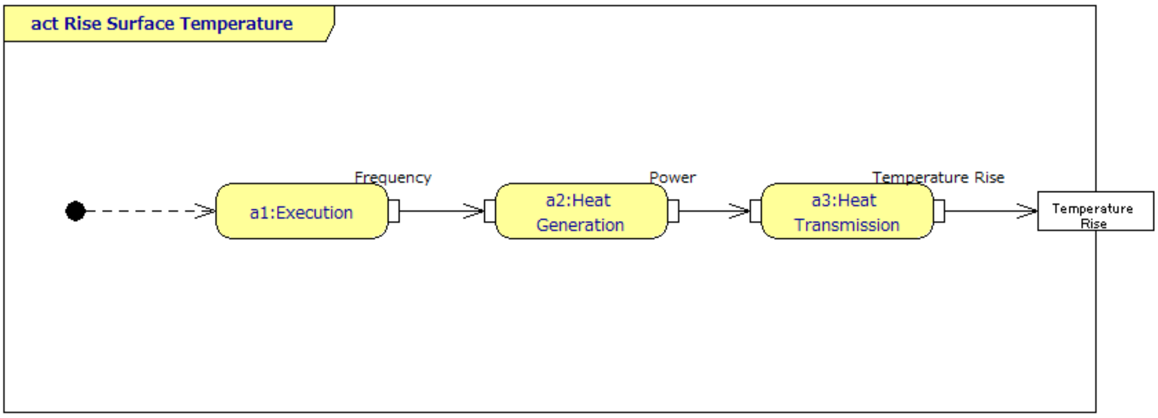

Figure 3. Activity Diagram related to temperature rise

Moritz and Henriques (1947) have experimented about low-temperature burn injuries using both human and pig’s skin. The temperature of 44 °C is considered as a minimum temperature that caused burns with contact over six hour period. For the temperature range between 44 °C and 51 °C, increments of 1 °C reduces the burn time by one half. Temperatures above 51 °C can rapidly cause burn injuries. 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 5 h. Roy (2012) proposed a maximum allowable surface temperature for electronic products, and referred to different maximum temperatures that were mentioned in various standards of products in an effort to prevent burn injury.

Figure 4 shows the temperature curve that considered burns occurred in Moritz’s study. If the power consumption is constant, the temperatures of electronic products increase as shown in the curve in Figure 5. After a certain period of time, the temperature rise reaches its maximum steady-state value. Therefore, the temperature rise after a short period of use may not cause burn injury during operation. However, if the temperature is as low as 44 °C, users may not consider the temperature to be very hot and can unconsciously continue to operate or hold a product prolong. Small electronic products, such as portable devices that a user can hold or bring in a pocket for long period, can cause burn injury under certain operating conditions. In this study, for the following thermal design case, the maximum temperature limit is set as 44 °C, which means that the target temperature rise is 19 °C at an ambient temperature of 25 °C to ease the risk of burn injury, for instance.

2.3 Simulation model

In this section, the temperature rise is modeled considering both the internal design valuables of module design and ITVs, which are boundary conditions between modules. Figure 6 shows a block diagram of electronics product models. Each activity shown in Figure 3 is allocated to modules described as blocks. To satisfy product quality requirements, the mechanical structure has constraints regarding the temperature rise to prevent burn injury. The constraints include that the surface temperature must be lower than the target temperature that causes burns. Internal design variables are described as values in modules. Those values are used in the calculation of ITVs that are transmitted between activities. The first activity is the load assignment. However, this only entails the setting up of the frequency *F* of semiconductor, and the software should be designed to work properly in the processing frequency. The second activity is about heat generation. The power *P* is calculated in Equation (1) with internal variables, which are physical capacitance of semiconductor *C*, voltage *V*, and frequency *F* assigned by software.

$$P=CFV^2 \tag{1}$$

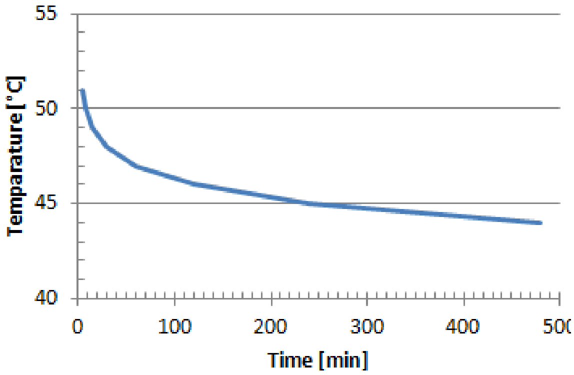

Figure 4. Temperature to cause low-temperature burn injury (Adapted from Moritz)

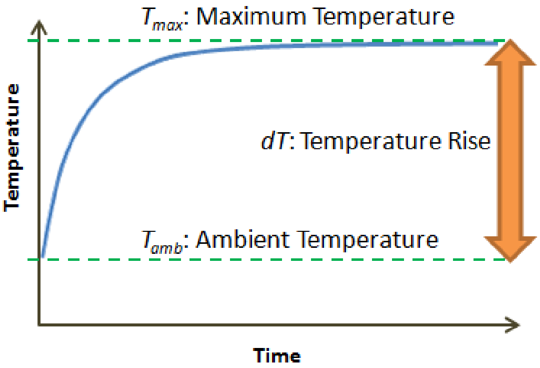

Figure 5. Typical curve showing temperature ris

This equation is simplified and based on the switching power dissipation of the CMOS (Chandrakasan and Sheng et al. 1992). It also assumes that semiconductors are fully activated at that frequency. The final activity is about transmitting heat. This calculation is based on Equation (2).

$$dT=P/(hA_{surf}) \tag{2}$$

In this equation, the temperature rise *dT* is calculated using the internal variables: thermal transfer coefficient *h*, surface area A_{surf}, and power *P*. This equation is based on the assumption that the thermal conductivity throughout the entire structure is uniform. As a result, those activities produce a temperature rise, which is a difference between the ambient temperature T_{amb} and the surface temperature *T*, as shown in Equation (3).

$$dT=T-T_{amb} \tag{3}$$

In SysML, a parametric diagram is used to simulate and evaluate how constraints are satisfied. In Figure 7, temperature rise is calculated in the parametric diagram regarding the constraint using internal design valuables. In the diagram, there are three constraint properties that are related to each module design and activity. Each constraint property has an algorithm for the calculation, and they are the same as the related equations stated above.

Using ITVs, the module designs are well collaborated. Each module is designed to satisfy ITVs as a target condition using parameters of internal design variables. When there is a design change, ITVs are updated to satisfy the constraints.

3 CASE STUDY

Applying the system-level thermal model, the specification of electronic products can be determined to satisfy constraints in order to prevent burn injuries for two applications. After calculation of initial design parameters, the system-level simulation is again used to propose alternative scenarios for improvement. In this chapter, we discuss the benefits of this approach in the case when the design change involves addition of an application.

3.1 Initial conditions

In this case study, a small-size electronic product is designed with constraint to prevent burn injuries. Two semiconductors are installed on it as electronics parts. P_1 and P_2 are the powers of semiconductors, and the power of the system is the sum of P_1 and P_2, as described as Equation (4).

$$P = P_1 + P_2 \tag{4}$$

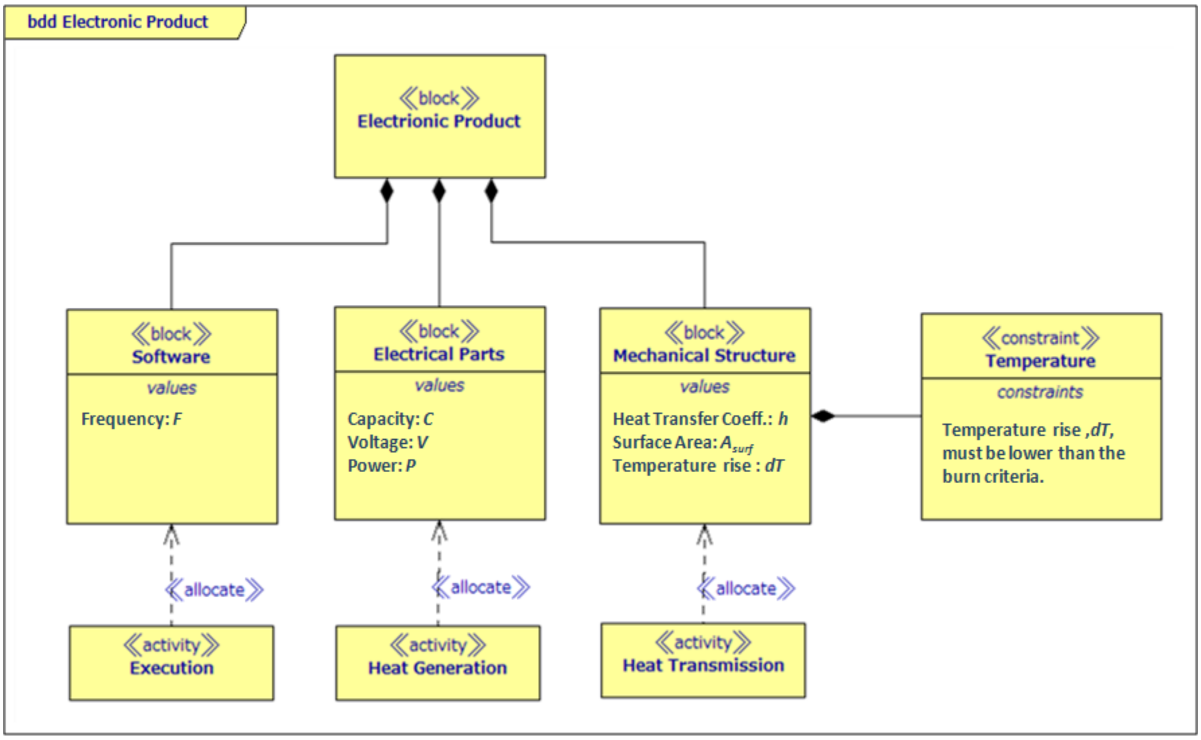

Figure 6. Block diagram of electronic products

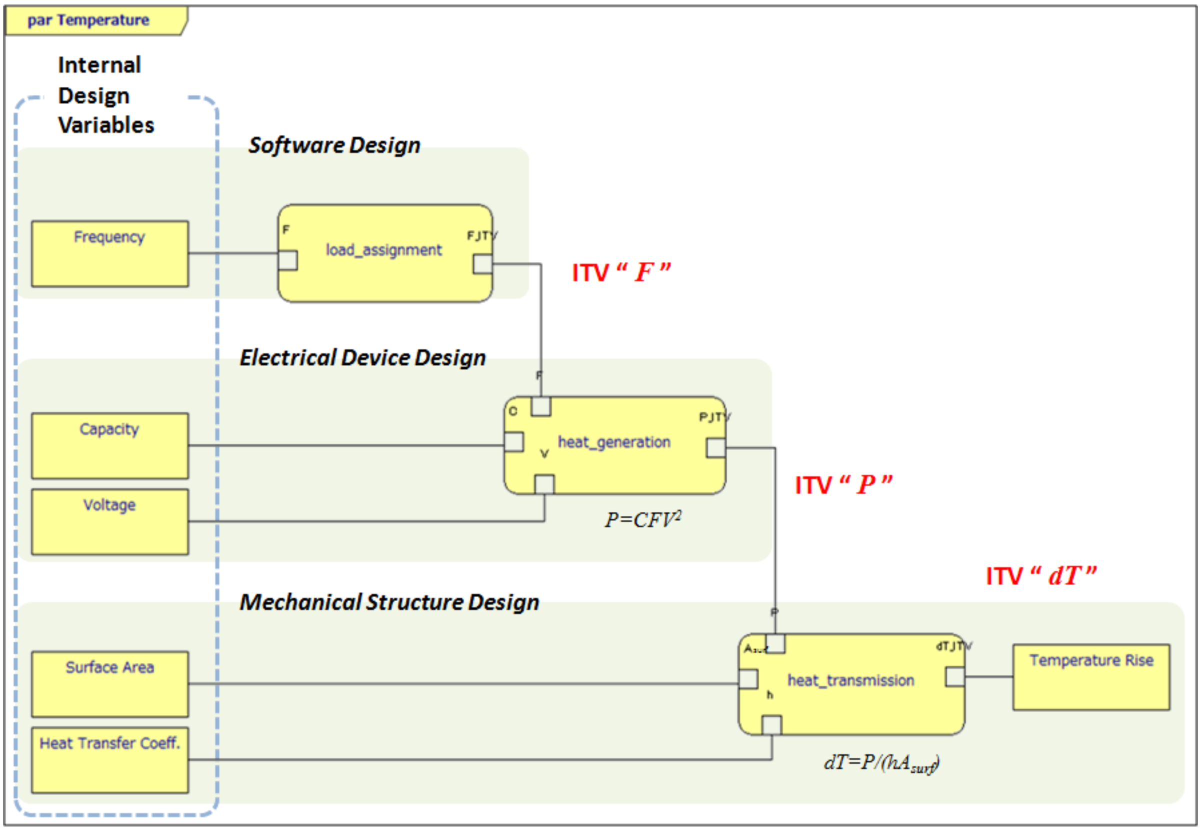

Figure 7. Parametric model of constraint about temperature

In Equation (1) that describes the power dissipation of the CMOS, P_1 and P_2 are described using Equations (5) and (6).

$$P_1=C_1F_1V_1^2 \tag{5}$$

$$P_2=C_2F_2V_2^2 \tag{6}$$

Table 1 shows the initial design parameters, which are the internal design variables and ambient temperature, for instance. Each semiconductor 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 *P* and temperature rise *dT* are calculated in following section.

Table 1. Initial design parameters

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_{surf}	35×50×10 mm
	h	12 W/(°C ·m2)
Environment	T_{amb}	25 °C

3.2 System-level simulation

In this section, two applications, A and B, are assumed such as video games and video encoding. The frequency *F* of ITVs is determined for two semiconductors. Then, the remainder of ITVs is subsequently calculated as shown in the parametric model in Figure 7. The first calculation of ITVs is shown in Table 2. To eliminate the possibility of burn injury, the surface temperature *T* must be below 44 °C in this case study. As shown in the table, the surface temperature *T* of application A is 43.1 °C which is lower than the temperature criteria. 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 criteria; moreover, a user can be burned during operation. Figure 8 shows the variation of temperature required to cause burns, as shown in Figure 4, 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.

Table 2. First calculation result of ITVs

Application	A	B
ITV F_1	820 MHz	700 MHz
F_2	80MHz	450 MHz
P	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)

Then, we propose counter measures to improve the temperature of application B by recalculating ITVs. Three alternative scenarios are shown in Table 3. 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 550MHz, the surface temperature *T* decreases to 42.5 °C, which is lower than the criteria. Second, the power *P* 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 2.7V, the power *P* in ITVs decreases to 1.12W. Then, the surface temperature *T* also decreases to 43.0 °C, which is lower than the criteria. The third scenario is that the temperature rise *dT* in ITVs is reduced by changing the mechanical structure, thereby expanding the product size. If the thickness of the dimensions of the enclosure is extended from 10 to 14mm, the surface area A_{surf} increases. Then, the surface temperature *T* also decreases to 43.2 °C, which is lower than the criteria. Those coupling calculations at the system-level do not require complicated models. With this system-level approach among modules, design changes can be discussed using the proposed alternative scenarios that have changes in each module. The benefit to product development is described in the following section.

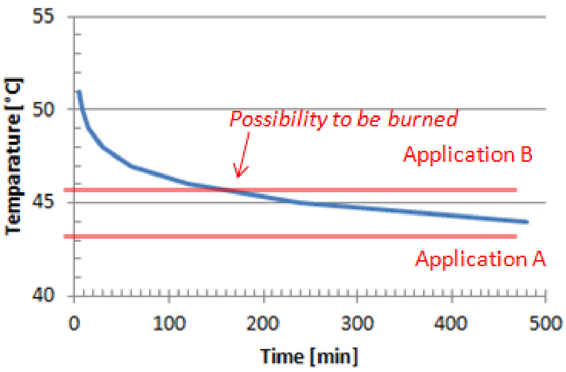

Figure 8. Thermal risk of applications A and B

Table 3. Alternative scenarios to improve the surface temperature of application B

	Original (Application B)	Countermeasure		
		Senario1	Senario2	Senario3
The module to change design	-	Software	Electrical Device	Mechanical Structure
Changed Internal design variable	-	F_1: 700 -> 550 MHz	V_2 : 3.6 -> 2.7 V	A_{surf} (Thickness): 10mm -> 14mm
ITV F_1	700 MHz	550 MHz	700 MHz	700 MHz
F_2	450 MHz	450 MHz	450 MHz	450 MHz
P	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

3.3 Benefit to product development

For the module design, sub-system-level simulations based on Computer Aided Engineering (CAE) are commonly used to determine the specification before detail design. However, the sub-system simulation is sufficiently accurate to predict the structural behavior of a module in a certain condition, assuming that the condition may be different during actual operations, especially if conditions are not well coupled among modules.

Figure 9 shows an example of a product development schedule using system-level simulation. In this example, there are two applications, A and B, which are already described in the previous section. The design of application A is started as early as other module designs. Because the system-level simulation model is simple, and its calculation cost is much less than that of sub-system simulation, the thermal risk can be evaluated at an early stage of product development. To deal with software changes, such as the implementation of an additional application B in the middle of the development schedule, recalculation of ITVs helps to determine alternative scenarios for the design changes. To assigning ITVs to module design, boundary conditions between modules are coupled. Each module can be developed using sub-system-level simulation based on the ITVs. Then lowest configuration items (LCI) of the sub-systems are developed. If the conditions are varied such that additional applications are implemented owing to the flexibility of installation or market demand, the product development has to involve changes to the design. Software upgrades and the installation of applications are often performed, especially for consumer electronic products.

4 CONCLUSIONS

This study described the development of thermal design specifications to satisfy product quality considering software changes. In the system-level simulation, ITVs are calculated as boundary conditions among module designs, which are software, electrical parts and mechanical structures. We quantified the risk of obtaining burn injuries and coupled simulations for activities between modules,. We also simulate the effect of making changes to the design.

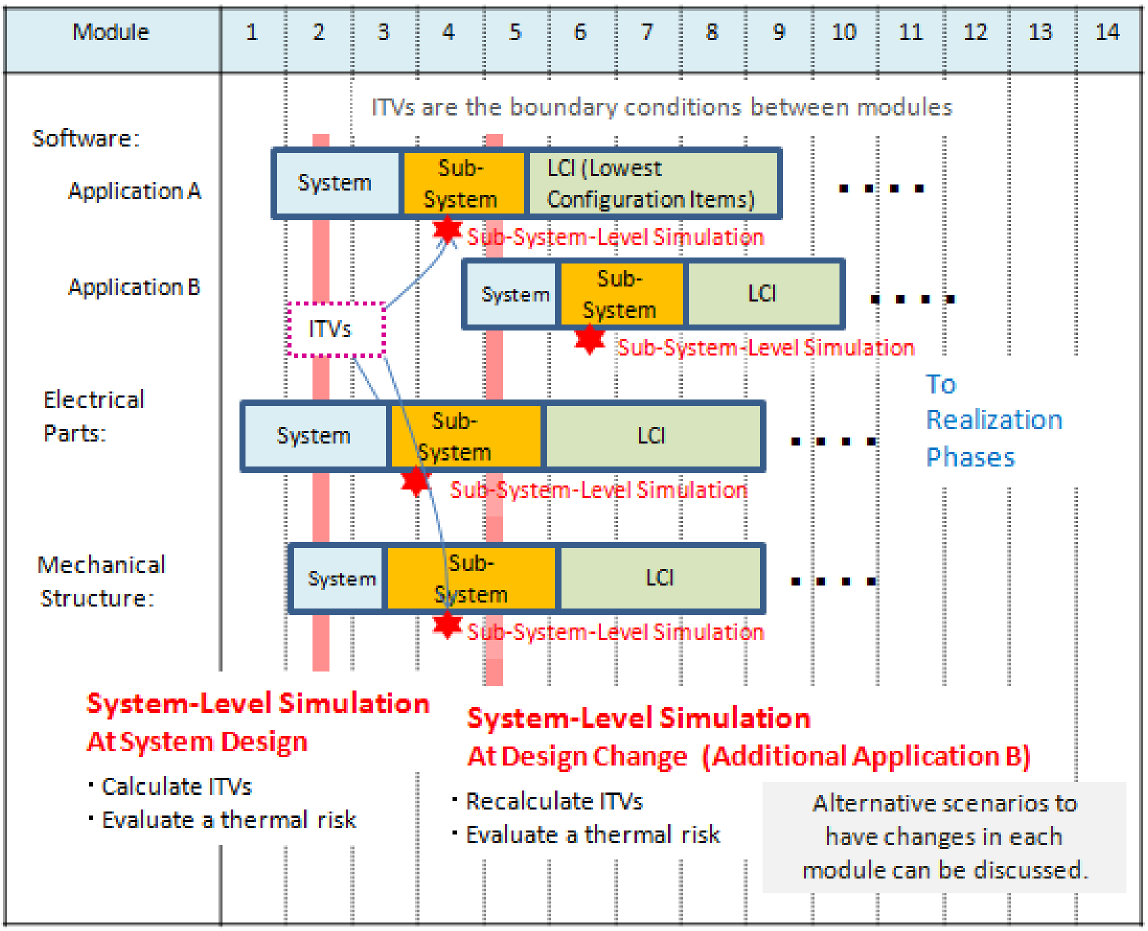

Figure 9. Product development schedule with system-level thermal simulation

We investigated the use of a thermal simulation model that uses SysML at the early stage of product development to support the collaborative designs of modules. By assigning ITVs to module design, boundary conditions between modules are coupled, and the thermal risk for applications can then be predicted. This thermal level simulation can be used in both system design and the design changes. For electronic products that have software changes, such as having additional applications, the recalculation of ITVs helps to realize alternative scenarios involving changes to the design in order to prevent thermal burn injuries. With this system-level approach among modules, design changes can be discussed using the proposed alternative scenarios that have changes in each module. This design approach can be used to satisfy both product quality and performance according to the market demand. The benefits for product development include the reduction of the number of iterations to develop thermal design specification.

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