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Planning of distributed design strategy with Design Structure Matrix/Domain Mapping Matrix

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Abstract

International workshare for the design of consumer electronics is rapidly increasing due to the diverse market demands in different countries, and advantages in labor cost. However, several concerns have been identified as major factors that hinder the quality, cost, and delivery (QCD) of product design in the so-called distributed design project. It is strongly desired to establish a structured design method that guarantees both the originality and quality of product design. This paper proposes a design framework that eliminates inconsistent performance of system components (modules) due to lack of communication between design sites. Module interconnection parameters in a system level are determined using the behavior coupling matrix and work distribution matrix, Initial design target (ITVs) for system tentative system boundary conditions shall be provided to each module design. The system decomposition using ITVs would work well as a framework for designing a product considering the overall behavior as a system where each module is designed independently at a different design site.

Introduction

Thermal design for consumer electronics. The Controlling thermal characteristics has become a common issue, which is critical for satisfying desired functionalities in various fields, and even architectural and thermal designs are now considered as one of the fundamental technologies used in for the development of various products. As shown in Table 1, which summarizes design attributes that are typical in different industries and products, consumer electronics stand out in terms of the variety of specifications (to satisfy the requirements of different countries throughout the world) and production quantity. In addition, the time allotted for product development, including planning, designing, manufacturing, and marketing, is very little and this makes the design of consumer electronics more difficult.

Table 1: Attributes of four industries/products

Industry	Market	Product Architecture		Design Mgmt.
	Production volume (#unit/year)	Complexity (# parts)	Customization (#product family)	Global workshare
Aerospace	Small	*Large*	Low	Medium
Automotive	Medium	*Large*	*High*	*High*
Consumer Electronics	*Large*	Small	*High*	*High*
Construction/HVAC	Small	Medium	Medium	Low

Global engineering and challenges. International distributed project for the design of consumer electronics as an individual product development is rapidly increasing due to the diverse market demands in different countries, system of supply chains from procurement to distribution, and advantages in labor cost. In view of the various reviews of collaborative design efforts across different countries and businesses taking place today, the following have been identified as major factors that hinder the quality, cost, and delivery (QCD) of product design in the so-called distributed design environments.

- Lack of communication due to the time difference and physical distance.
- Unevenness or disparity in skill and experience of the experts employed between design sites.
- Maldistribution of experts (each site does not have experts in all areas).

Due to these risk factors faced especially in the design of complex and difficult models, recent development shows some cases in which there are more disadvantages than advantages inherent in the division of labor. However, such disadvantages would not usually show up in the conventional scheme for centralized design effort because everyone understands the culture and rules particular to a locale. Therefore, it is strongly desired to establish a structured design method that guarantees both the originality and quality of product design, i.e., a method that yields quality design for products with a distinctive feature and value.

When there is a problem in the product design wherein required characteristics are not obtained (poor convergence) after prototyping in a distributed design project, and an iteration of work, such as redesigning, is necessitated; poor performances in terms of thermal characteristics, acoustic noise, and unwanted radiation (EMC) are the common problems observed. Figure 1 shows a typical configuration of consumer electronics, which includes a lot of heat dissipating modules in the thin/small enclosure.

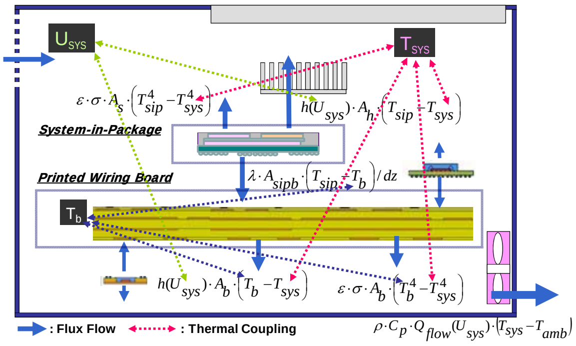


Figure 1. Typical configuration of CE products.

In several cases, modules such as semiconductors, printed circuit boards, and other devices are the basic unit for the division of design effort. However, in order for the completed product to operate as a system, it is necessary to consider the thermal interactions depicted in Figure 1 from the early design stage. Distribution of design makes it difficult to discuss the subject between different locales, and this is the major reason why iteration of design work is often required as stated above. In other words, an issue that affects the overall performance of a product depending on the internal space (field) of a product, in addition to the characteristics of each module and component, will be a significant risk, especially in product groups that are thin and miniaturized. Therefore, a new framework is desired to make the designing easier for a particular product category in an internationally distributed design paradigm.

Independent thermal design for managing unplanned iteration. In the study of product design processes, Hayashi et al. had focused on semiconductor modules and proposed a method for finding an optimum performance balance (trade-off solution) for an optimum design implementation problem by studying the method to determine optimum solution for coordinating the circuit design and thermal design. However, this study is limited to modules consisting of semiconductor devices and does not address the possibility of different devices being designed in different countries by division of labor.

On the other hand, several studies have been carried out on methodologies for obtaining the optimum module configurations by making overall tasks in a product design visible by the use of design structure matrix (DSM) and similar techniques. For example, Greiner et al. have studied the performance of the fuel injection system for engines, analyzed dependencies between modules from the perspective of components, and evaluated the results to develop a strategy for designing modules. Similar efforts to analyze complexity of structures and obtain the optimum module configuration are in progress. However, there are not many studies that propose concrete principles of design by assuming distribution of designing tasks and addressing design issues involving conflicting situations of modularization and physical coupling among modules.

In the study carried out by Leung, a risk analysis method for distribution strategy has been proposed from the perspective of designing an international collaboration. Although the objective is similar to that of this study, Leung’s study mainly addresses how to assign respective modules to different design sites (selection of an optimum distribution scenario) and does not make any reference to a concrete design framework for overcoming various issues arising from distributed design, including evaluation of overall system architecture and detailed design of sub-systems. Studying the methodology in this area is the purpose of this study.

Based on the above discussion, this paper evaluates the design methodology that enables stabilization of interactions arising from physical coupling on the system level for designing products, for which development takes place at multiple design sites, especially for ultra-thin and miniaturized products that have high degrees of complexity and difficulty. In particular, this paper proposes a design framework that eliminates inconsistent performance of system components due to lack of communication between design sites, and also eliminates iteration of work to correct such inconsistencies completely by developing a thorough model of system performance, including thermal and noise characteristics, considering allocation of the module design to different sites and setting up tentative system boundary condition for each module in advance at an early stage of the system design.

Methodology

The Controlling thermal characteristics has The methodology used for decomposing the design and preventing iteration of work can be described as follows:

-Depict the physical couplings between modules by using a behavior model.

-Understand the couplings between module design sites from the module design team allocation plan.

Based on these two views, initial target values (ITV) are assigned for system tentative system boundary condition of particular modules whenever necessary before proceeding to the detailed design of each module. By analyzing the module coupling conditions using design structure matrix (DSM) and domain mapping matrix (DMM), it will be possible to assign temporary ITVs systematically to each distributed design team. DSM is an analytical representation that allows the representation of structural dependencies of objects, tasks and others using a matrix representation. DMM is an enhancement of the DSM methodology to inter-domain matrices which presented relationship among different domains such as the analysis between modules and their design sites in this paper’s application.

This will also create a framework for designing a product considering the overall behavior as a

system where each module is designed independently at a different design site.
Figure 2 illustrates this module decomposition concept. The details are described in the following sections.

Behavior coupling matrix.

Figure 3 describes the energy transmission between modules using the system description language SysML in a sequence chart format. In case of a thermal design, it is interpreted as a system's heat budget that represents the thermal interchange between system modules and the balance of the heat of exchanged in the system. The values denoted on top of arrows, which represent the energy flow, indicate the heat exchange volume [W] for respective module interfaces and are added only when the value can be estimated at the time of architectural design.
Once the behavior model is described for the product's behavior in terms of thermal and acoustic noise, it will be possible to develop a DSM of physical correlations (behavior coupling matrix) between modules, as shown in Figure 4.

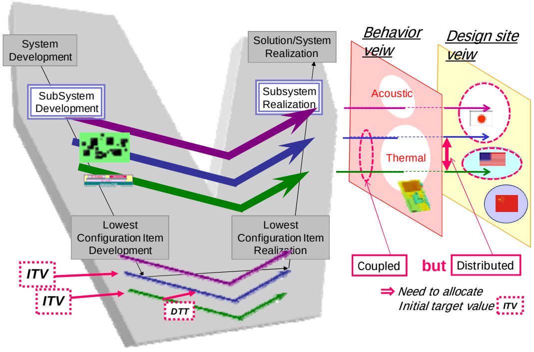


Figure 2. System decomposition considering behavior and design site

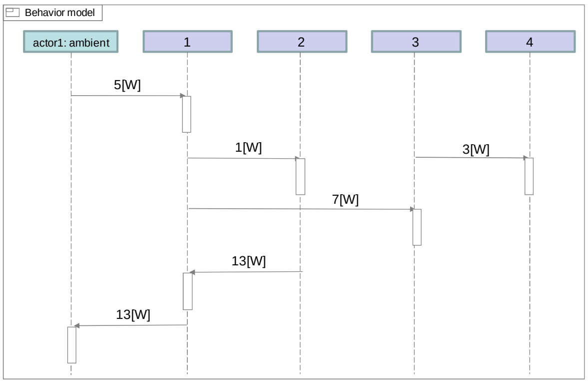


Figure 3. Behavior model (thermal)

		Module						
		1	2	3	4	5	…	N
Module	1							
	2							
	3							
	4							
	5							
	…							
	N							

Figure 4. DSM of behavior（Behavior Coupling Matrix）

Work distribution matrix.

The system architecture shall be reviewed at an early stage of product design process. The design site allocation will start when the configuration of modules is finalized. Figure 5 shows a format for summarizing the relationships between modules and their respective design sites in the form of Module Design Site DMM.
By multiplying this matrix by its transposed matrix, DSM of design site (work distribution matrix) can be obtained in a matrix form similar to Figure 4. From the "physical characteristics" and coupling conditions of respective "design sites," it will make it possible to set up temporary ITVs necessary for each distributed design team. Then a system decomposition from the modules to

sub-components shall be performed in the process described in the following section.

		Design site			
		A	B	C	…
Module	1				
	2				
	3				
	4				
	5				
	…				
	N				

Figure 5. DMM od design site

Module interconnection parameters (Initial design target, Design target transfer)

Initial target values

The ITVs are tentative values of the system thermal boundary conditions for each module whose exact values can only be obtained with a physical prototyping or a system-level thermal simulation. However, from a knowledge database based on past product developments or approximate calculations using product macro-models, we can prepare practical ITVs for each module-thermal design. These numbers may provide a reasonable interface among modules in the system. Using above-mentioned Behavior Coupling Matrix, we can easily identify the thermal interactions among modules that may be grounds for creating an appropriate ITV. Using ITVs, considering the effect on the system, each design team can optimize its module design.

Design target transfer

The ITV is a scheme to use tentative values for thermal boundary conditions (the correct value can only be identified later in the verification process). Another important factor in thermal design information exchange is feedforward interactions.

For examples, the design of semiconductors and other module designs may be sequential (semiconductors design starts first in many cases). Therefore, rigorous communication is essential to produce globally optimized designs. This study proposes the design target transfer (DTT) concept, which consists of forwarding multiple design targets to the next subsystem design step. SiP design engineers can prepare multiple sets of PWB temperatures that correspond to the burden of the SiP design. In the subsequent PWB design stage, PWB engineers may consider their design in these cases and investigate the trade-offs in thermal treatment costs between the SiP and PWB levels. Eventually, because ITVs and values obtained through DTTs may bridge the gap between the designs of coupled modules, unnecessary iterations in interdependent tasks may be avoided, thus leading to a globally optimized system.

System decomposition considering module coupling relationships

When there are physical couplings between modules, and simultaneously respective modules are developed at different design sites, there is an increased risk of iteration of works at downstream processes due to the difficulty of system characteristic evaluation in distributed design schemes. Therefore, modules for which assignment of tentative system boundary condition in system operation are determined using the behavior coupling matrix and work distribution matrix, ITVs for system tentative system boundary condition shall be provided to each design site to which the design of a particular modulet is assigned. This process is described as follows:

- Define a behavior model for performance requirements (temperature, sound pressure, etc.).
- Prepare a DSM for the physical correlations between modules.
- Prepare a DMM for the relationship between modules and design sites and convert it to a

DSM of design site correlations between different modules.

- Determine the modules for which temporary values (ITV) for tentative system boundary condition are provided.

By following these steps, it will be possible to prevent performance defects at downstream processes due to physical couplings between modules, and thus, reduce iteration of works.

Methodology

Audio/video product

The system decomposition method considering module couplings described in the previous section is applied to the design of audio/video product shown in Figure 5. The subject case was developed based on a record of the design process for an actual product developed in a distributed design environment, and by applying the proposed design framework; the study aims to verify the possibility and effectiveness of the framework.

Modules subjected to the case study are semiconductor elements SiP1 (system in package), SiP2, ASIC1 (special application LSI), printed circuit boards PWB1 and PWB2, the enclosure, and the “cavity” that represents internal space and determines the characteristics of thermal and acoustic fields. During the actual implementation, there had been some iteration of design works, including the semiconductor design, PCB design, and overall layout of modules, before completing the design process and proceeding to the manufacturing stage.

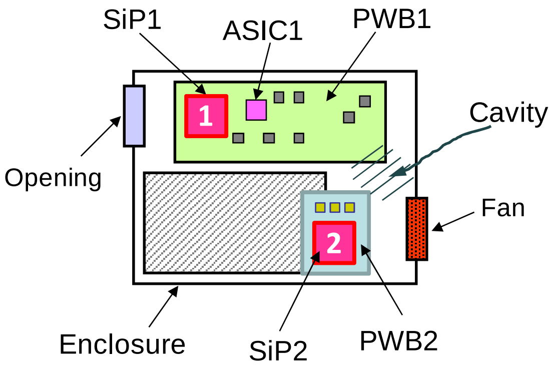


Figure 6. AV product

Formulation of DSM of behavior (behavior coupling matrix)

Figure 7 shows a behavior model in terms of the cooling function. It describes heat exchange/transfer with the external air and thermal interchange between modules using the format of SysML sequence chart. Next, the behavior coupling matrix shown in Figure 8 was developed based on the model for modules in question. Although the behavior model introduced in Chapter 2 had a variation with description of energy amount, this case study uses a binary format that represents the existence and non-existence of module correlations.

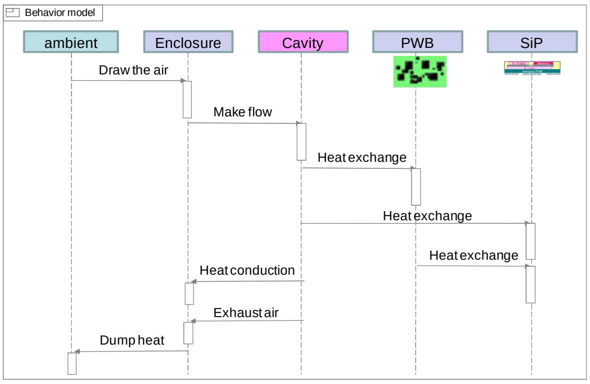


Figure 7. Behavior Model (Thermal)

	ASIC1	SiP1	SiP2	PWB1	PWB2	Cavity	Enclosure
ASIC1	1	0	1	1	1	0	0
SiP1	0	1	0	0	0	0	0
SiP2	1	0	1	1	1	0	0
PWB1	1	0	1	1	1	0	0
PWB2	1	0	1	1	1	0	0
Cavity	0	0	0	0	0	1	1
Enclosure	0	0	0	0	0	1	1

Figure 8. Behavior Coupling Matrix

Formulation of DSM of design site (work distribution matrix)

Figure 9 shows a DMM of the relationships between modules and design sites for the same product. The development scheme involves product planning and project management in Japan, development and procurement of semiconductor devices both in and out of Japan, the design and manufacture of printed circuit boards in Japan, and the design of final packaging and verification of system characteristics commissioned to an oversea EMS.In addition, this DMM is transformed to a DSM of design site (work distribution matrix) regarding the correlations between module design sites and shown in Figure 10.

	🇯🇵	🇺🇸	🇨🇳
ASIC1	1	0	0
SiP1	0	1	0
SiP2	1	0	0
PWB1	1	0	0
PWB2	1	0	0
Cavity	0	0	1
Enclosure	0	0	1

Figure 9. DMM of Module-Design site

	ASIC1	SiP1	SiP2	PWB1	PWB2	Cavity	Enclosure
ASIC1	1	0	1	1	1	0	0
SiP1	0	1	0	0	0	0	0
SiP2	1	0	1	1	1	0	0
PWB1	1	0	1	1	1	0	0
PWB2	1	0	1	1	1	0	0
Cavity	0	0	0	0	0	1	1
Enclosure	0	0	0	0	0	1	1

Figure 10. DSM of design site

Figure 11 shows a series of operations from analyses of module interactions and design-site correlations, the ITVs identified from the results, and the lower components within the modules that require detailed design.

For example, the behavior coupling matrix and the work distribution matrix can identify the necessary ITVs for the SiP thermal design as shown in the left top of Figure 11. The design of SiP1 will be conducted using ITVs (cavity's and PWB1's system boundary conditions) as described in right bottom of Figure 11.

By designing each module based on the system decomposition shown here, it is possible to prevent unplanned iterations of module design during downstream processes.

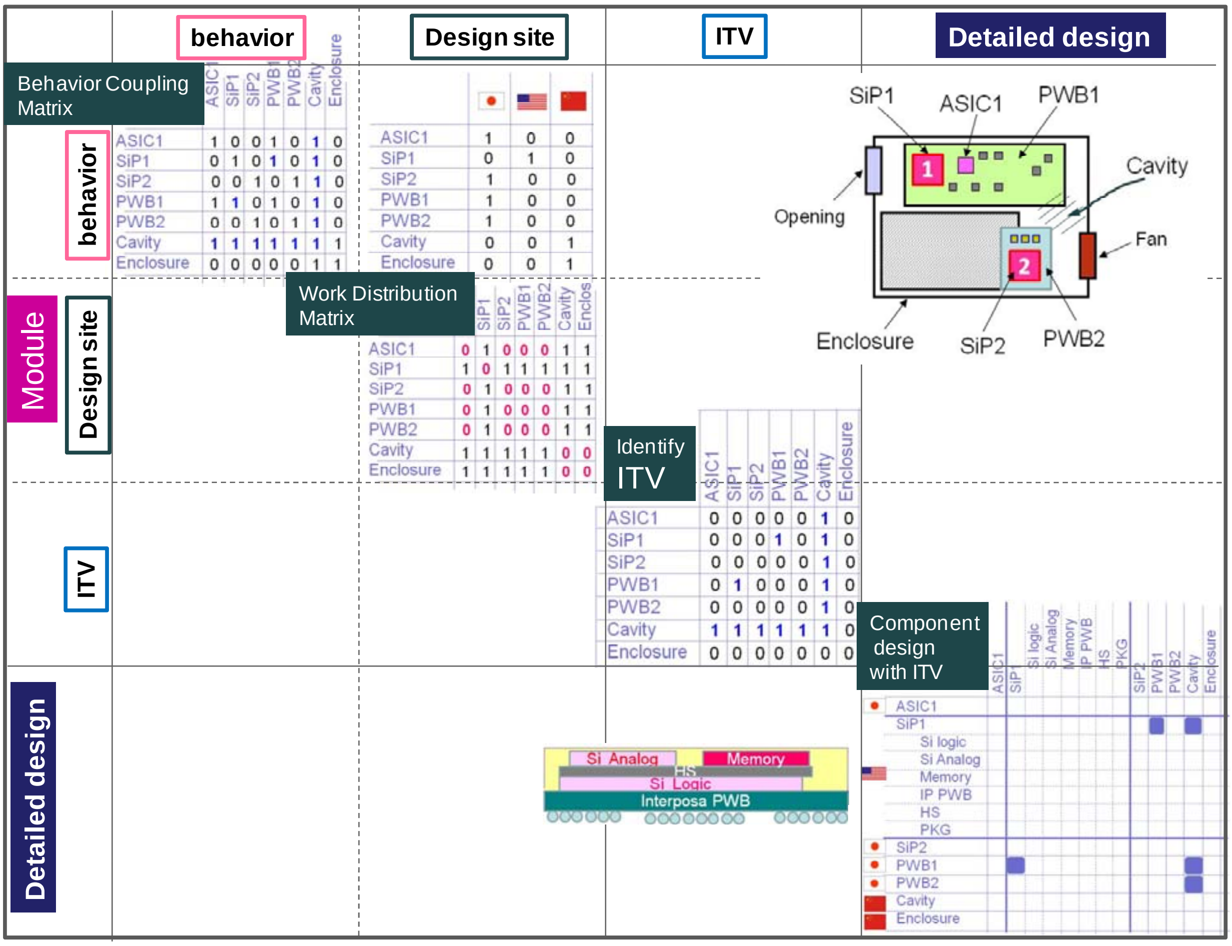


Figure 11. DSM and DMM for system Decomposition

Detailed module design in the distributed design site with ITV

In this case study, we demonstrate PWB module detailed design. After system decomposition, each design site starts actual design process using assigned ITVs. External boundary condition of PWB such as cavity air velocity and temperature is assumed to be values of ITVs, which is depending on the detailed design of enclosure, cavity and cooling fan etc. designed at other design site.

Figure 12 shows the comparison of PWB temperature of three cases. First one is original chip layout with ITV velocity condition, resulting the violation of performance constraint. Second one is result of same chip layout but with faster velocity, satisfying performance constraint, however flow velocity in the cavity must be much faster than ITV condition. The third one is modified floor-plan, determined after the discussion with electrical engineers in terms of signal integrity, with ITV condition (0.25 m/s velocity), concluding that this PWB module design would be satisfy system level performance.

Thermal Design problem (PWB module) :
To find design variables with module-level thermal simulation using “Initial target values” subjected to constraints of PWB temperature.

**Design variables:* Floor plan (layout of chips)
Structure (layers, materials)
**ITV:* Air velocity in the cavity (0.25m/s)
Temperature rise in the cavity
**Performance constraints (thermal):*
Temperature of solidar on the PWB
**Performance constraints (others):*
Signal integrity, EMC regulation etc.

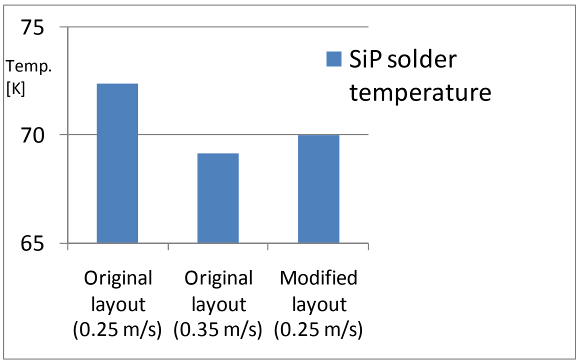
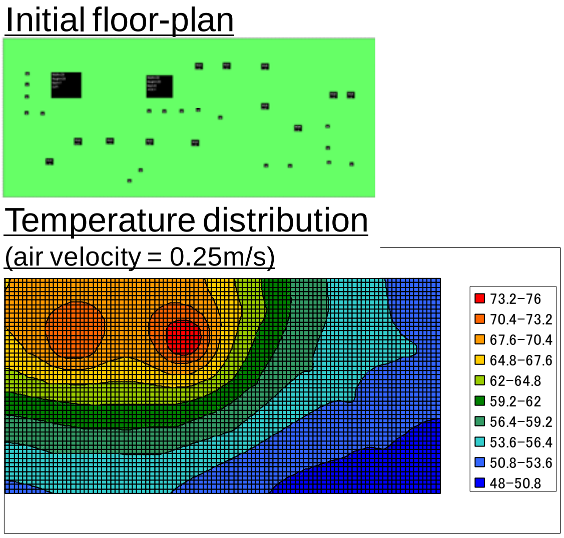
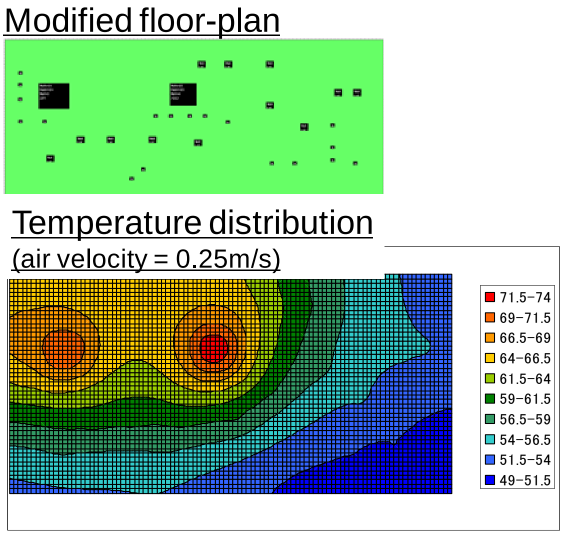


Figure 12. PWB temperature


Initial floor-plan

Temperature distribution (air velocity = 0.25m/s)

Figure 13. Module thermal simulation
(Initial)


Modified floor-plan

Temperature distribution (air velocity = 0.25m/s)

Figure 14. Module thermal simulation
(Modified)

In the traditional module design, the PWB is evaluated in open air or with the former product enclosure, which are not the precise conditions of the object designed, and these results is used to finalize module design, albeit with some ambiguity. These inconsistent design assumptions at each design site might lead design iterations at later stage of system realization. In our approach, at the product architecture phase, the behavior coupling analysis (thermal coupling identification) using module-level behavior modeling and the work distribution matrix can identify the necessary ITVs for the required modules. These quantitative thermal system boundary conditions can lead to optimal module designs at the system level, before system verification with the actual prototype, thus minimizing design iterations in later design stages.

Conclusion

In view of the various reviews of collaborative design efforts across different countries and businesses taking place today, the following have been identified as major factors that hinder the quality, cost, and delivery of product design in the so-called distributed design environments.

- Lack of communication due to the time difference and physical distance.
- Unevenness or disparity in skill and experience of the experts employed between design sites.
- Maldistribution of experts (each site does not have experts in all areas).

In order to establish a structured design method that guarantees both the originality and quality of product design. This paper proposes a design framework that eliminates inconsistent performance of modules in the system due to lack of communication between design sites. Module interconnection parameters in a system level can be determined using the “behavior coupling matrix” and “work distribution matrix.” The parameters “Initial design target (ITVs)” is tentative system boundary conditions which shall be provided to each module design. The system decomposition using ITVs would work well as a design framework for distributed project. The process is described as follows:

- Define a behavior model for non-functional requirements (temperature, sound pressure, etc.).
- Prepare a DSM for the physical correlations between modules.
- Prepare a DMM for the relationship between modules and design sites and convert it to a DSM of design site correlations between different modules.
- Determine the modules for which temporary values (ITV) for tentative system boundary condition are provided.
- proceed the each module detailed design with the ITVs and module level simulation tools.

By following these steps, it will be possible to prevent performance defects at later design processes due to physical couplings between modules, and thus, reduce iteration of works.

Case study of AV product design demonstrates the effectiveness of proposed methodology. This paper reports the development of thermal design framework that primarily focus on reducing the product development time. Another goal of this research is to incorporate a system modeling language to enhance the collaborative design framework presented herein.

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Biography

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