1 INTRODUCTION

In product development, the chosen product architecture often possesses characteristics of both modular and integral design. Within a modular architecture, a Function-Behavior-Structure (FBS) model has been applied to describe modules and their interfaces. To resolve emerging interface conflicts, several strategies based on both modular and integral action have been formulated. The strategies encompass TRIZ methods, as they focus strongly on product innovation. The purpose of the presented study is to combine TRIZ techniques and FBS modeling while trying to solve interface conflicts at a low level of abstraction. The interface conflict resolving strategies have been applied on an industrial case study successfully.

Keywords
TRIZ, Innovative Design, Product Development, Design Methodology, FBS modeling
to the overall manufacturing and production processes. In the end, this would result in a minimum investment to obtain the newly developed product.

Genrich Altshuller [6, 7] – the founding father of TRIZ – discovered through his patent research that innovation is a systematic process: creative solutions use already existing solution principles (or patterns). Many principles show that breakthrough solutions result from overcoming a contradiction. This contradiction usually presents itself at a low level of abstraction, or in FBS terms, in the structural space of the FBS model.

1.3 Electronic product design example
A striking example of this product evolution is the design of electronic products, as in this industry technology evolves at an enormous pace. In a typical architecture, such a product is split into two modular parts according to two functions: (1) the electronic function and (2) the cooling function. The former provides the product with its primary function, signal processing. The latter is required as a support function, due to heat losses that occur caused by the primary function. Figure 1a shows an example of such an electronic product, a graphics card. The electronic function of this device is to translate the input from the computer's (AGP) socket to an (VGA) output signal for a monitor or screen. The cooling function must prevent the graphics card from overheating.

The corresponding FBS model for this product is shown in Figure 1b. The electronic function is divided according to two independent (standardized) structures: (1) the Printed Circuit Board (PCB) and (2) the electronic components. Both structures are primarily governed by knowledge of electronics; although solid mechanics and heat transfer also play a role. The interface between both structures is mostly constrained by the layout of the components on the PCB.

The cooling function in this example is realized by a heat sink (and fan), for which its behavior can be described by heat transfer knowledge. The interface between the component and the heat sink is constrained by contradicting demands, which will be discussed in the next section.

This design – composed of the physical elements: PCB, electronic component and heat sink – is seen as a typical conceptual solution that can be used for many electronics products. Hence, for each new product, the same FBS model can be used and routine design can be applied; however, the interfaces must be validated each time. The fact that both the functions and the structures are kept as independent as possible is a logic often striving for, for instance in axiomatic design [8]. However, such an approach only promises high control over individual (modular) functional requirements.

1.4 Interface conflicts
In the development of electronic products, problems are currently arising due to the demand for more functionality. As this demand increases, so do thermal dissipations. Another trend is the continuous miniaturization of the electronic components themselves. To make things worse, both trends combined present a dramatic increase in power (heat) density on the surface of the electronic component. This is illustrated in Figure 2, where Intel microprocessors are arranged according to their power density and year of market entrance [9]. For a long time, the presented conceptual solution was used and routine design could be applied successfully. This mainly involved scaling the size of the heat sink according to the specifications of the electronic device. This is also shown in the figure by indicating the advised cooling device for some of the microprocessors.

This evolution of microprocessor technology is also referred to as Moore's law, as Moore predicted this – the doubling of the number of transistors in a chip each year – in 1965 already [10]. In his publication, Moore also predicted that cooling should not be a problem: "Since integrated electronic structures are two-dimensional, they have a surface available for cooling close to each center of heat generation." In relation to this quote it is interesting to note is that, for all the presented heat sink devices, the interface between the PCB and electronic component, and the heat sink has been maintained for more than 20 years of technological evolution.

The shrinking electronic components and the growing heat sinks are however a contradiction to both structures of the conceptual solution. The cooling function – a support function – should not impede the primary function; hence, further evolution of this product leads to a
(thermal) limit, as can also be deduced from the continuously increasing line in Figure 2. Beyond this limit, due to the increasing power density, heat sinks either grow out of proportion and do not fit into the product anymore, or they cannot dissipate the amount of generated heat anymore and subsequently the electronic component overheats. Hence, in both cases, the interface is breached and a change of the conceptual solution is imminent.

2 INTERFACE CONFLICT RESOLVING STRATEGIES

To deal with contradicting constraints, this study has identified five strategies to resolve emerging conflicting demands at an interface. The strategies emerged from the structure space of the FBS model and the effect that various solutions may have on this model. The solutions are categorized according to the TRIZ levels of solutions. Finally, the interface conflict resolving strategies, guiding the design engineer to a solution, are formulated as generic TRIZ problem solving patterns.

2.1 TRIZ levels of solutions

According to TRIZ research [11], there are 5 levels of solutions for industrial problems. 

- **Level 1** indicates a quantitative system change that is realized by altering some parameters within the adopted conceptual solution; for instance, the continuously growing heat sinks. As mentioned, in terms of FBS modeling, this is referred to a routine design.

- **Level 2** indicates a qualitative system change by improving an existing sub-system within the same structure combination (i.e. without changing the product architecture). The FBS model remains the same, however as a sub-system is fundamentally changed other interface issues may arise.

- **Level 3** indicates an innovative system change by realizing an invention. The product or system is fundamentally improved and contradictions are resolved. Hence, some of the interfaces of the FBS model are removed by a Level 3 solution.

- **Levels 4 and 5** finally indicate a pioneering invention and the discovery of a new scientific principle, respectively. For this study, where the focus is on resolving interface conflicts, these two levels of solutions are not directly pursued.

TRIZ research [12] has also shown that 32% of industrial engineering solutions are acquired by routine design (Level 1). However, 63% of industrial engineering solutions are solved by Levels 2 and 3 solutions. Finally, the last 5% of solutions are of Levels 4 and 5. In other words, if routine design fails – the topic of this paper – 93% of all solutions are of Levels 2 and 3. Hence, the conflict resolving strategies are formulated according to the effects of Levels 2 and 3 solutions.

The strategies are formulated according to the TRIZ problem solving patterns. In TRIZ, these patterns are used to guide the engineer in the likely directions, as extrapolated by years of patent research, where he may find solutions to his problem. These patterns are formulated as abstract directions. In FBS terms, a similar approach is strived for as design engineers should be guided in possible directions to resolve interface conflicts.

2.2 Generic TRIZ problem solving patterns

As mentioned, the interface conflict resolving strategies, guiding the design engineer, are formulated as generic TRIZ problem solving patterns. An example of such a TRIZ pattern is Inventive Standard 1-2-1, as shown in Figure 3. The standard graphically describes a concept solution to block a harmful effect between parts A and B. According to the figure, the engineer is stimulated not to try to remove the harmful effect, but rather to focus on making sure the harmful effect does not reach the other part.

For the conflicting interfaces of the modular product architecture, a similar approach is used. The solution patterns are formulated as abstract strategies in the structure space of the FBS model. Also, in this case, the idea is that the engineer or designer is stimulated to think according to the presented strategies. The strategies involve either modular or integral action. All five strategies are graphically described in Figure 4 and each is elaborated upon hereafter.

![Figure 3: Generic TRIZ problem solving pattern (Inventive Standard 1-2-1) [11].](image)

![Figure 4: Interface conflict resolving strategies.](image)
2.3 Outline of the strategies

When investigating the TRIZ Inventive Standards, Standard 3-1-4 (the convolution of systems) was identified as a possible means to change the solution direction into the use of more integral action. This integral action is clearly visible in Figure 5. The efficiency of bi- and polysystems can be improved by integrating several components into a single component and by reducing auxiliary components [11].

![Figure 5: Generic TRIZ problem solving pattern (Inventive Standard 3-1-4)](image)

Strategies 3-5 have been defined based on the pattern of Standard 3-1-4 and adhere to the integrative approach. Strategies 1 and 2 (as elaborated below) describe solutions that remain true to the modular approach. Here the modification applied can be linked to more than one innovative principle. Both for the integral as for the modular strategies other innovative principles could have been chosen.

The first strategy, Strategy 1, focuses on one part of the interface and can thus be classified as modular action. If another structure can be found for this part that fulfils the required function, the interface can be preserved. The part on the other side of the interface can also be maintained.

Strategy 2 basically is the same as Strategy 1; however it focuses on the part on the other side of the interface. Both strategies should be applied first before moving on to Strategies 3-5, because there is minimal impact to the product architecture. Hence, if another part structure is found, rapid product development – as is a quality of modular action – is possible.

Strategy 3 tries to find other structure for one part that fits inside the structure of the part on the other side on the interface. If such a structure can be found, the interface can be removed and a new integrated part is developed. Hence, this is defined as integral action.

Strategy 4 is again the same approach as Strategy 3 with the focus shifted to the structure of the part on the other side of the interface. Finally, Strategy 5 is the most cumbersome strategy, as here two new structures must be found that fulfill the two previously separated functions. This is also considered integral action. Because it is easier to focus on one part, Strategies 1-4 are preferable over this strategy. However, sometimes the designer has no choice but to handle according to this strategy.

Referring back to the TRIZ levels of solutions, Strategies 1-2 can be classified as a “Level two solution”. Hence, the FBS model and its interfaces remain; although other criteria may be formulated. Strategies 3-5 are typically a “Level three solution”; hence, a contradiction is solved and the interface is removed.

3 INDUSTRIAL CASE STUDY

The presented interface conflict resolving strategies have been applied on an industrial case study. The case study was related to electronics cooling in a military application. Due to the increasing demand in power, the conceptual solution (identical to the FBS model of Figure 1b) to design the power module was failing. Heat sinks were growing out of proportion and the module could not be fitted into the system anymore. In other words, the product architecture failed and innovative action was required.

The presented strategies have led to a number of new concept solutions to overcome the interface conflicts. The remainder of this section discusses each of the strategies to construct the power module in a new way. For all strategies, Part A in Figure 4 refers to the heat sink structure in Figure 1b; whereas Part B refers to the PCB and electronic component structure.

3.1 Strategy 1

Strategy 1 implies to find another structure that fulfills the cooling function. Figure 6 shows a solution in line with this strategy. In this case the heat sink is replaced with another cooling device that gives a better performance, for instance heat pipe cooling. No change is required for the PCB and the electronic components. This concept solution is already used extensively in the industry, for instance for notebooks or high performance graphics cards. Hence, for the power module of the military application it is an interesting candidate.

![Figure 6: Use of heat pipes as alternative cooling device](image)

3.2 Strategy 2

As the cooling function is the bottleneck, Strategy 2 implies to find another structure that still fulfills the electronic function and simultaneously augments the cooling function such that the heat sink structure can be maintained. Figure 7 shows a solution in line with this strategy. By manufacturing thermal vias (metal filled through holes) in the PCB, heat can be transported through the PCB more efficiently. Now, for instance, two heat sinks can be applied. One on the top side of the component and one on the bottom side of the PCB. No changes are required for the heat sink. Note that, scaling or using 2 heat sinks as proposed, is regarded as routine design and has no influence on their conceptual solutions.

![Figure 7: Use of thermal vias to transport heat to other locations on the PCB](image)

This concept solution is also already used extensively in the industry. Adding additional amounts of metal and using thicker metallic layers to construct the PCB is in fact generally seen as a genuine method to enhance cooling capabilities through board structures [13]. Needless to say, this is not very weight efficient.
3.3 Strategy 3
Strategy 3 implies to find another structure that fulfills the cooling function and can be integrated into the PCB and electronic component structure. Following this strategy it was observed that in fact the solder connection, connecting the electronic component to the PCB, can also be utilized as a heat exchanger. By injecting cool air directly underneath the electronic component, heat can be extracted from the bottom side of the component. This approach is illustrated in Figure 8.

![Figure 8: Patented innovative air cooling concept.](image)

Only a through hole in the PCB is required to inject the coolant. As drilling is already an established process for PCB production, this does not change anything to its structure. The new heat transfer device is truly integrated into the PCB and electronic component.

As a result of this research, this concept solution was patented in 2009 [14].

Following the approach of Strategy 3, another method of solving the thermal issues was found. Instead of the previously mounted heat sink, the heat can also be transported by means of two-phase cooling (e.g. a heat pipe) manufactured directly inside the PCB structure. This solution principle is shown in Figure 9.

![Figure 9: Patented innovative integrated heat pipe cooling concept.](image)

Two-phase cooling technology is integrated inside the PCB structure. The device is constructed inside the laminated structure that makes up the PCB and dissipated heat can be transported through the PCB very efficiently. Also for this concept all utilized process steps are established steps for PCB production and no changes have to be made to its conceptual solution.

This concept solution was also patented as a result of this research in 2007 [15].

3.4 Strategy 4
Strategy 4 mirrors the previous strategy and searches for another structure for the PCB and electronic component that still fulfills the electronic function and fits inside the heat sink structure. Figure 10 shows a solution in line with this strategy. A very large heat sink, also known as a coldplate, is used to cool and position the components. Hence it takes over the function of the PCB to hold and position the components.

![Figure 10: Use of coldplates as a cooling device.](image)

The electronic components can be connected together directly or through small PCBs. This concept solution is also already used in the industry, for instance to cool high power transistors.

3.5 Strategy 5
Strategy 5 is, as mentioned, the most cumbersome strategy. Two new structures must be found that maintain the electronic functions and can resolve the thermal issues. Figure 11 shows a solution in line with this strategy.

![Figure 11: Patented innovative liquid cooling concept.](image)

By circulating a coolant through the PCB and underneath the electronic component, heat can be extracted from the bottom side of the component by means of single phase cooling. This requires a sealed enclosure to be manufactured between the PCB and the component. Also, the fluid lines inside the PCB must be leak tight in order to prevent coolant from penetrating the board structure. Currently, these are not standardized operations.

This concept solution is not yet industrially implemented; however, seeing the potential for future applications, this concept was also patented as a result of this study [14].

As illustrated, all approaches have led to new insights and novel concept solutions. In fact, three of the presented concept solutions have been patent protected as a result of this study. From an industrial perspective, especially the first four approaches are interesting as then at least one modular structure is preserved. In the end, this saves cost during the development and production phases. The fifth approach requires a rigorous change in both modular structures. First, between the PCB and the component a sealed enclosure must be designed. Second, reliable (non-leaking) fluid lines need to be engineered.
4 CONCLUSION

Strategies to overcome critical limits that may occur during the development of products are presented. The product is described by a modular architecture based on a Function-Behavior-Structure (FBS) model. Due to the evolution of the individual modular parts, sometimes interfaces cannot be maintained. This causes the standard conceptual solution to fail and consequently routine design cannot be applied anymore. Changing to a new concept (i.e. innovation) is imminent.

To resolve emerging interface conflicts and find novel conceptual solutions, 5 strategies have been presented. The strategies are adopted from TRIZ techniques and are formulated as abstract solution principles, applying either modular or integral action. The strategies were used on an industrial case study, which led to the identification of several new concept solutions. As a result of this study, three high potential concepts were patent protected.

REFERENCES


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