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Unveiling fundamental relationships in industrial product development

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Abstract

Identification and clarification of relationships between product properties is fundamentally important in industrial product development. The process is however frequently perceived difficult. The presented research aims at clarifying if a visual tool can provide help in this work. The tool is a combination of previously known techniques and has so far been implemented at two product developing companies. Results and reactions from the tests are hitherto positive and the conclusion is therefore that this extended casual diagram can be a useful addition to the product developer's toolbox.

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Keywords: Causal diagram, trade-off curve, limit curve, product development

1. Introduction

A substantial part of industrial product development work is about redesigning existing products. An example of this is presented in a survey from the UK industry [1]. Various tasks can amount to anything from a slight modification or facelift of an existing design to a further development and extensive improvement of the product, which perhaps also includes a technology change. In these activities it is important for the design team to understand how the product works at present, how its different parts interact, what properties of it that the customers and other stakeholders value the most, how these properties are related, the physics behind the technologies employed and what is known, or perhaps not known, about those [2].

A company may of course have low awareness of and knowledge about several of these relationships in their existing products. They have designed, built and sold a product that "works". But product development is in practice sometimes not so much based on rigorous analytical work and detailed experimentation, i.e., fact-based decisions, as on more "practical" reasoning, estimates, rules of thumb, gut feelings etc., i.e. on other things than pure facts. This may be because the company simply lacks the competence or resources required to work in a knowledge-based fashion, but it may also be because they have for one reason or another developed a bad habit of cutting corners in their development work. In any case the result is that they have limited knowledge, or at the worst no substantial knowledge at all, of how a change in any of its properties would affect the behavior of the product. And the result of a change in several will then of course, if possible, be even more obscure. Will it go unnoticed, will the product behave slightly differently or will it cease to work altogether? The designers will neither know how much different, nor what properties can be changed before the product starts to behave dramatically different, what the limits of the applied technologies are and, consequently, what the solution space looks like. I.e., within which interval is it possible to change each variable?

Any attempt to change and/or redesign a product in a situation like the above will of course be a highly haphazard process with an unpredictable outcome. In order to be able to carry out predictable product development work, all critical *knowledge gaps* must be located and closed before the design work commences.

Without access to powerful tools, particularly in cases with complex designs, it is difficult for the designers to see the full picture and understand what is important and should be

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prioritized when they alter a design. The consequence is that they may instead work on parts and aspects of the product that are less important when it comes to what they want to accomplish, or they attempt to solve problems that there already exist solutions to. In extreme cases, designers may be unaware of what is actually *not* well-known or understood about the product function when they change the technology, and therefore ought to be attended to.

Due to the properties of the human brain, visualization is often useful both to create an overview of something as well as to highlight details and connections in a larger pattern. This paper proposes a technique and a visual aid for product developers which combines several existing tools to accomplish this. The technique can guide product developers in their work as well as in discussions with customers on which product properties ought to be changed in a redesign process, and how to do that, i.e., which different sub properties should be altered. The tool has been tested at two product developing companies with promising results. The paper concludes with a discussion of how the tool can be further developed.

2. The research process

The setup is a multiple case study [8] of mechanical design with two main industrial design cases. The objectives were to clarify how causal diagrams can improve the understanding of a product or system, if they can provide a framework for storage and display of design knowledge and also to formulate a prescription for how to introduce the new tool in an industrial environment.

Since the researchers were actively involved in the studied process, it differs from the description of Yin [8] in that it involved a portion of action research [9]. The reason for using action research was to develop, introduce and evaluate a new design methodology which the participants of the study did not have sufficient knowledge to apply on their own, i.e. without the support of the researchers. The study was a joint venture between industries, Chalmers University of Technology and the research institute Swerea IVF AB as project manager. Empirical information was collected in four workshops, and by interviewing the participants.

The research process was inspired by the Design Research Methodology (DRM) that is used to develop design support [7]. DRM is based on four stages:

- Research Clarification
- Descriptive Study I
- Prescriptive Study
- Descriptive Study II

The process started with a hypothesis that causal diagrams would provide valuable support in the design process. To verify this idea a literature study was conducted in the Research Clarification stage. The result was that there is no good research results of how to implement a process for creating causal diagrams in practice, or what the effects of such diagrams might be, even though the concept is mentioned in Ward [6]. This indicated that a need for the suggested support existed. In order to be able to judge the practical usefulness of the proposed technique, four *success indicators* were formulated and are presented in Table 1.

Table 1: Indicators of successful research in this study.

Success indicators	**Description**
1	Does the methodology create a better understanding of the product than the current way of working in the company does?
2	Do experienced engineers accept the methodology as a new way of working?
3	Do experienced engineers accept the results that the methodology generates?
4	Can a firm use the methodology without the support from researchers?

The Descriptive Study I activities were carried out by the researchers and aimed at participants' understanding of causal diagram methodology to the extent that they were able to identify which parameters are important for its success and how these interact.

The findings from the Descriptive Study I formed the basis for the Prescriptive Study, in which the new *extended causal diagram* and the working process that together form the suggested support were worked out. In order for an extended causal diagram to constitute a framework for the product knowledge, apart from the important parameters with their interactions, it also has to display information on the causality and nature of the interactions (see below). On top of that, it shall also visualize the interactions in the form of e.g. trade-off curves as well as highlight critical knowledge gaps. It is not uncommon that engineers are unaware of the existence of the latter until they come to this step in the process.

The support developed in the Prescriptive Study was evaluated in a Descriptive Study II in industrial workshops in two different firms. One researcher introduced the working process and the extended causal diagram, and together with a colleague also observed the workshops and took notes to document them.

3. State of the art

There exist a number of tools which can be used both to help identify and in different ways illustrate relationships between product properties. Examples are Quality Function Deployment (QFD) [10], function analysis, causal diagrams [5, 6] and trade-off curves [4, 6]. Substantial work of relevance has also been done in the field of engineering change management. One example of this is the contribution by Rutka et al. [3].

Figure 1 is an example of the type of causal diagram discussed in this paper. It illustrates the structure of a laptop PC. This type of causal diagram shows four kinds of information:

- which properties that characterize the product (in square boxes)
- how these properties interact (lines between boxes)
- the causality of each interaction, i.e., if property A is changed, property B changes too. Example: if the battery cells in Figure 1 become heavier, so does the whole PC if nothing else changes. But the inverse is not necessarily true, i.e., that a heavier PC implies that the weight of the battery cells has increased (arrows at the ends of the lines)
- the nature of each interaction, i.e., if a change in property A drives property B in the same or the opposite direction numerically. Examples: a higher battery cell weight increases the PC weight, so the latter is positively related to the former (a plus or minus sign on each line)

negative by some riders since the bike gets heavier, but note that such a statement would be a highly subjective one. The interaction is still objectively *positive* in the sense above.

Trade-off curves are widely used to create Pareto sets in design optimization [11]. Causal diagrams are thoroughly described in [5]. The combination of the two is treated in [6]. The latter presents what seems to be the most visual and comprehensive way of applying trade-off curves and causal diagrams such that it is easy to understand by practitioners in a stressed industrial environment where quick decisions have to be made. A literature research has indicated that little scientific work has been carried out in this area on the type of products that the firms participating in this work specialize in. This justifies the research work described in this paper.

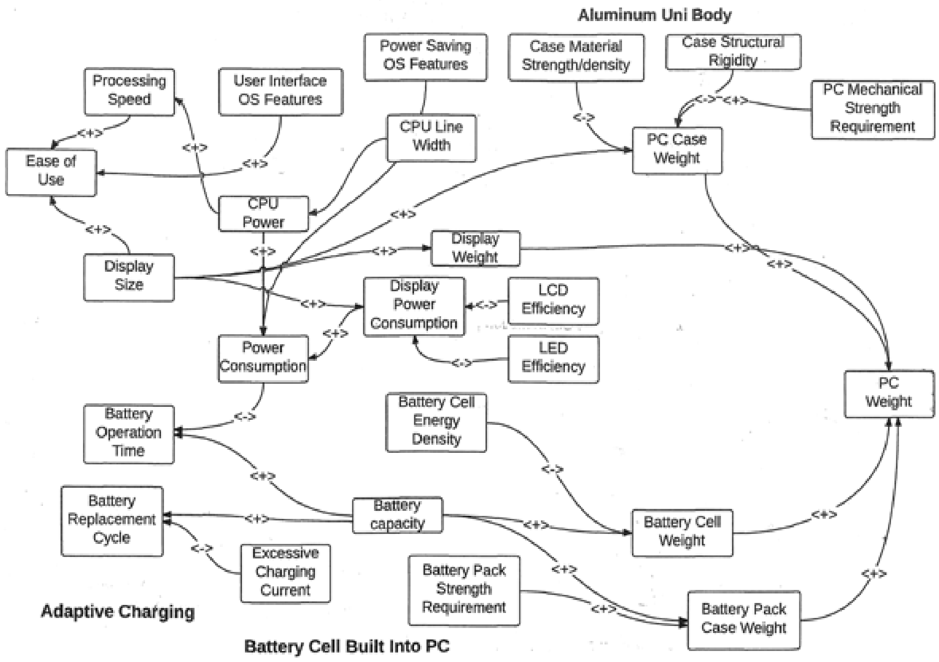

Figure 1. An example of a causal diagram of a laptop PC as an illustrative example. Courtesy of Kimio Inagaki.

If an interaction is considered positive or negative depends on the view adopted. It is recommended to adhere strictly to physical laws and relations since this produces the more objective results. That is to say that if the numerical value of something changes in a positive direction as a result of a positive change in another property, the interaction between them is considered positive. For properties that can be measured and assigned numerical values, the results are independent of who carries out the measurements, given that the person is generally competent in the particular field of work.

As an example, consider the tubes of a bicycle frame. If we make them thicker, the tubes and thereby the whole bicycle gets heavier. This interaction may surely be perceived

4. The extended causal diagram

A causal diagram is a suitable framework for displaying various kinds of information which is important to pay special attention to in the product development process. Examples are e.g.:

- properties regulated by laws, standards etc.; i.e. they cannot (at least not easily) be changed outside certain intervals
- properties which are difficult to control in a robust manner in production
- constraints on the product imposed by the production system

- properties which competitors are good at
- properties which the company has previously had problems with
- selling point properties
- specific customer application properties which the sales force often discusses with customers
- other properties of interest not regulated by laws, i.e. some of environmental importance
- trade-off curves displaying contradictions between properties
- possible ranges of applicability of property variables
- knowledge gaps and properties in need of further investigation

As an addition from the subject of Set-Based Concurrent Engineering [12], it is also possible to display more detailed knowledge on how properties are related to each other wherever relationships exist. It could e.g. be in the form of trade-off or limit curves (see Figure 2) that visualize a contradiction between two product properties. This is something that engineers often encounter and which is an obstacle in product development work. A limit curve marks the boundary between two areas in a diagram, e.g., where possible solutions exist and where they do not. It is not unusual that a curve at the same time is *both* a trade-off *and* a limit curve.

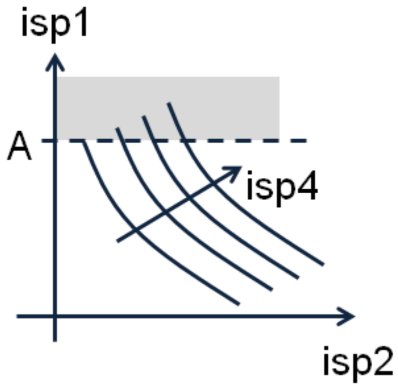

Figure 2. A trade-off curve for properties *isp1* and *isp2*. The diagram also includes a limit curve, since the level of isp1 is not allowed to exceed A. The curves can be associated with the causal diagram in Figure 3.

Figure 3 shows a causal diagram similar to the one designed from the application of the sliding door case in paragraph 5.

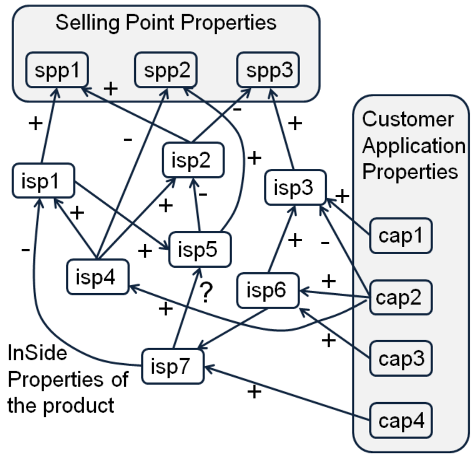

Figure 3. The principal layout of a causal diagram

The diagram contains three types of product properties, namely:

- Selling Point Properties (spp1, spp2 and spp3)
- Customer Application Properties (cap1 – cap4)
- InSide Properties (isp1 – isp7)

Selling Point Properties are properties that the customer values and therefore often wants to be as high or as low as possible. A typical example is energy use, which should of course be minimized. Customer Application Properties are connected with the application of the product in the customer's setting. This could typically be a power supply that is fixed to 230 volts and maximum 10 ampere. InSide Properties are properties of the product that are not directly displayed to the user. An example is the friction inside a transmission of a product that affects the energy use when operating the product. The properties of the product interact according to the arrows which connect them in Figure 2. The principles of the interaction are described in paragraph 3, State of Art. If we assume that spp1 should be as low as possible, we must strive to lower isp1 and isp2 since they both have a positive influence on spp1. Isp1 is however influencing isp2 through isp5 such that isp2 increases when isp1 decreases, so we have a contradiction since both properties cannot be minimized at the same time. They are influenced by isp4, and if that increases, both isp1 and isp 2 increase, which is visualized in Figure 3 and Figure 2. A question mark designates the connection between isp7 and isp5, meaning that designers have little or no knowledge of how isp7 influences isp5, so here is a knowledge gap that has to be closed in order to fully understand the product.

5. Practical applications of an extended causal diagram

The proposed tool – an extended causal diagram – has been tested and validated at two firms that design and manufacture mechanical products.

At the first firm the problem at hand concerned an automatic sliding door of the type found at store entrances, with two glass sections that move horizontally in opposite directions. The firm had a general knowledge of how the more important characteristics influence each other, but had previously not attempted to determine all properties of the system and how they interact. Two product developers together with two external researchers, who helped them, worked one day to establish a preliminary causal map of the door. The staff of the firm later refined and further extended this map and managed to identify system properties and interactions that had previously been considered unimportant or unknown. They also highlighted properties of special interest to discuss with the customers (Customer Application Properties in Figure 3), building a foundation for producing better information for their sales force. The work helped them to clearly see which other properties affect those of particular interest, and where they have knowledge of the interactions or need better to understand how properties influence each other. One example of this is the connection between isp7 and isp5 in Figure 3. This has in turn provided a basis necessary for the designers to be able to understand which areas they should concentrate their improvement efforts to.

The causal diagram also highlighted where the designers needed to make trade-offs between critical parameters that affected the performance of the product (see principal curve in Figure 2). And, unless they already possessed the needed facts, they got a picture of what knowledge was necessary for them to obtain through e.g. testing. Knowledge of this type can to a great advantage be displayed as trade-off curves and also in other types of diagrams support the dialog with the customers.

At the second firm the problem was about a complicated mechanism that is operated by a lever. No causal diagram of the system existed at outset, and due to the complexity of the product it would have been a very demanding task to make a complete one. It was therefore also difficult to analytically derive how a property of high importance to the customer depends on properties further down the structure. A piece of information dearly wanted was how the motion of the lever affected the operation of the mechanism. These two properties were quite a distance away from each other in a simple sketch of a causal diagram, in the sense that they were not directly interacting with each other, but the figure itself suggests that one way of modeling this interaction would be to consider the mechanical work done to the system by the torque on and the turning angle of the lever, see Figure 4.

Just the examination of a problem by drawing a causal diagram can thus produce an idea of how to solve it without explicit understanding of all intermediate relationships between the sub properties of the system.

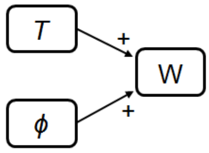

Figure 4. The causality between the mechanical work (W), the torque (T) and the turning angle (ϕ) of the lever.

The mechanism does not store any energy, so the mechanical work needed to supply to change its state is entirely dissipated by friction. The work delivered by the lever is the torque on it, T, multiplied by the angle ϕ through which it turns. A constant value of this product, i.e. corresponds to a particular state of the mechanism.

$$\boldsymbol{T} \cdot \phi = \text{constant} \qquad (1)$$

The visual relationship between the torque on the lever and the angle for constant work is a trade-off curve, see Figure 5.

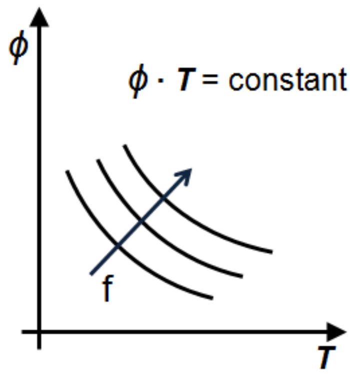

Figure 5. A trade-off curve for the torque (T) on and the turning angle (ϕ) of a lever. f = internal friction in the system. Higher friction leads to a shift in trade-off curves.

Any point on the curve corresponds to a particular state of the system in that it is related to the same amount of work delivered to it. Another state of the system corresponds to another, similar and parallel trade-off curve given by another constant. Each state is possible to attain via a certain combination of torque (T) and turning angle (ϕ), as given by its trade-off curve.

There is a contrasting difference [8] between the case with the sliding door and the case with the lever mechanism. In the former, the causal diagram was drawn to show the interaction between individual subsystems. In the case of the lever mechanism, a higher abstraction level was chosen regarding the mechanism as a black box, and the relations between the parts of the mechanism were not described. For this reason the expression (1) was used to describe the relation between the torque (*T*) and the turning angle (ϕ), and the causal diagram was created after that. There are no knowledge gaps at this abstraction level of the mechanism. In the case with the sliding door, the creation of the causal diagram can proceed and support the description of the interactions of the individual subsystems.

6. Discussion

6.1. Reliability

The research work was in each case performed by two researchers. Data collection was done by taking notes, asking questions, collecting narratives and taking photos. There are no contradictions in the collected material or in the views of the researchers. The results were reported back to the participating firms to confirm that their observations and conclusions were the same as the researchers'. A representative from one of the firms in this study has reported the results as a positive achievement in a meeting with other companies that participate in the same research project but are not part of the study. These circumstances contribute to the reliability and validity of the results.

6.2. Generality

The study was carried out on mechanical and electromechanical assembled products in Swedish companies to test and validate the ideas of combining causal diagrams and trade-off and limit curves. The outcome of the tests was appreciated and put into practical use by the individuals taking part in the study from the case firms. this strengthens the validity of the results. The results are likely to be valid within the cultural context at hand, i.e., Sweden. The firms that participated in the study belong to the same multinational corporation. A representative with global responsibility for process improvements in the corporation has scrutinized the results and agrees to the conclusions. This fact implies that the results are probably valid also for cultural environments outside Sweden.

6.3. Further development

With today's computers, it would be feasible to make a three-dimensional causal diagram. Such a body of visual information could be turned and rotated on the screen to make it easy to study, and provide much more space than a two-dimensional diagram for displaying the extra information suggested above in section 4.

7. Conclusion

The research fulfills the success criteria in Table 1 in the following ways: The extended causal map creates a better understanding of the product in the sense that it reveals unknown relationships. Furthermore, it encourages the user to quantify relationships in numbers and describe them as curves in order to illustrate them in the causal map. The combination of causal diagrams and trade-off curves is a powerful and simple tool that can unveil fundamental relationships between product properties in industrial product development. The use of the methodology helped both companies in the study to gain new knowledge about critical aspects of their products. One firm used knowledge from the causal map to communicate performance properties of its products both internally and in the form of an external sales tool.

The methodology is rather easy and quick to introduce, and it does not require the researchers to be present after its implementation. It was quickly accepted as a new way of working in the firms, and the results from the applications were perceived as highly relevant by experienced engineers.

Connecting to the last sentence in chapter 3 where this research is justified, the scientific approach of this work and the fulfillment of the success criteria in Table 1, it is clear that the results add a novelty to the scientific literature.

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References

[1] Huang GQ, Mak KL. Current practices of engineering change management in UK manufacturing industries. International Journal of Operations & Production Management 1999; Vol. 19, No. 1, pp. 21-37.
[2] Ström M. Improving engineering change processes by using lean principles. Gothenburg: Chalmers University of Technology; 2013.
[3] Rutka A, Guenov MD, Lemmens Y, Schmidt-Schäffer T, Coleman P, Rivière A. Methods for Engineering Change Propagation Analysis. 25th Congress of the International Council of the Aeronautical Sciences. Hamburg; 4-8 September 2006.
[4] Maksimovic M, Al-Ashaab A, Sulowski R, Shebab E. Knowledge Visualization in Product Development using Trade-Off Curves, Proceedings of the 2012 IEEE Conference on Industrial engineering and Engineering Management (IEEM). Hong Kong; 10-13 December 2012.
[5] Pearl J. Causality: Models, Reasoning, and Inference. 2nd ed. New York: Cambridge University Press; 2001.
[6] Ward AC, Sobek DK. Lean Product and Process Development. Cambridge: Lean Enterprise Institute; 2014.
[7] Blessing L, Chakrabarti A. DRM, a Design Research Methodology. Heidelberg: Springer; 2009.
[8] Yin RK. Case Study Research: Design and Methods, 4th ed. Thousand Oaks: Sage Publications; 2009.
[9] Oosthuizen MJH. Action research. Chapter 9 in: Research Methods for Students, Academics and Professionals: Information Management and Systems. 2nd ed. Wagga Wagga: Elsevier; 2002.
[10] Akao Y. Quality Function Deployment - Integrating Customer Requirements into Product Design. Cambridge: Productivity Press; 2004.
[11] Papalambros PY, Wilde DJ. Principles of Optimal Design Modeling and Computation. 2nd ed. New York: Cambridge University Press; 2000.
[12] Sobek DK, Ward A, Liker J. Toyota's Principles of Set-Based Concurrent Engineering. Sloan Management Review 1999; 36: p. 67-83.