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APPLICATION OF AXIOMATIC DESIGN TO ELECTRIC BICYCLES

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ABSTRACT

Market conditions and the situation inside electric bicycle producing companies require a product development process which ensures that customer requirements are met and problems in product design are identified at an early stage. Therefore, this research takes an analytical approach towards the development of electric bicycles by applying Axiomatic Design, which offers both a holistic framework for product development as well as analytical mapping in between the individual steps of the design process. The application is done as a case study at a German electric bicycle manufacturing company and based on a collection of customer feedback as well as the contribution of the company's management. In the design process, functional requirements and design parameters are formulated and a design matrix is created to identify and resolve coupling issues. Further, constraints such as price, weight and ease of use are taken into account and process variables for practical implementation are suggested. The study results in recommendations for a specifications sheet of a new electric bicycle model. It is concluded that Axiomatic Design is of substantial advantage to the case company's product development. Future research is suggested to improve the level of detail and quality of electric bicycles designed by Axiomatic Design.

Keywords: axiomatic design, electric bicycles, market requirements specification

1 INTRODUCTION

A central issue in product design is the fulfilment of customer needs. At the same time, efficient engineering of products is important to avoid rework and reduce product life cycle cost. Both of these factors are especially true for the development of electric bicycles at Third Element GmbH & Co. KG (further referred to as 'Third Element'). First, the market for electric bicycles is rapidly growing, dynamic and diversified (ZIV 2013: 63). This makes it challenging to design products that successfully address customer needs, especially for small companies such as Third Element, which do not have the resources for extensive market research. Second, it is crucial for those companies to organize their development processes in an efficient way in order to avoid rework. Recalls of electric bicycles and bankruptcies of firms in the industry have shown that the complexity of electric bicycles is often underestimated and mistakes in their design are recognized too late (myStromer: 2013).

Axiomatic Design has the potential to address both of these issues. The importance of customer needs is addressed by putting customer feedback at the very beginning of the design process and effectiveness is pursued by taking an analytical approach to transform those requirements into functions and physical properties of a product. The advantages of this methodology are better matching of product functions with customer requirements, better consistency in between functions and physical parts and, thus, more efficiency and less cost during the life-cycle of a product (Axiomatic Design Solutions 2014).

There are numerous studies connected to electric bicycle design using other methods than Axiomatic Design. Hsu, Liu and Chan (2012) have studied power management of electric bicycles based on reinforcement learning. Xiao, Liu, Du, Wang and He (2012) have applied topology optimization to frame design of electric bicycles. Wu and Sun (2013) have designed and analysed a novel speed-changing wheel hub with an integrated motor for electric bicycles, using analytical modelling. Liang, Lin and Chang (2006) have used a fuzzy logic and single chip approach to develop an intelligent control for electric bicycles. Hua, Kao and Fang (2011) have designed a regenerative braking system for electric bicycles by experimenting with digital signal processing. Further studies apply Axiomatic Design to the design of non-electrical bicycles, for example the case study conducted by Guo, Jiang, Zhang and Tan (2012). However, little research has been done on the combination of Axiomatic Design and electric bicycles.

In order to fill this gap and to explore how Axiomatic Design can help to deal with the issues in the field, two questions are addressed in this study: "How does an Axiomatic Design based electric bicycle look like?" as well as "What are the opportunities and limitations of Axiomatic Design with this case?" The first question marks the main goal of this study, the creation of a proposal for an electric bicycle which fulfils the needs of Third Element's customers in the best possible way. The second question aims at a brief evaluation of the approach taken, possibly helping the case company with the decision on further pursuing this matter.

In the following, information on the background of this case is presented. Subsequently, the data collection is described, followed by the application of the Axiomatic Design framework: The formulation of functional requirements, design parameters, process variables and constraints as well as the creation of a design matrix. Finally, the results of this process will be presented and discussed.

2 BACKGROUND

This research is based on the case of Third Element, an original equipment manufacturer (OEM) of electric bicycles located in Gauting, greater area of Munich, Germany. Third Element was founded in 2009 when prototypes of a newly developed electric bicycle were tested. This model combined a full suspension mountain bike with a powerful electrical assist, which was an innovation to the market at the time. In 2011, the company received the official listing from the Federal Office for Motor Traffic Germany as a certified manufacturer, enabling the company to series production also of such electric bicycles that require a type approval. In 2012 Third Element presented a new model line-up, adding hard tail mountain bikes and bicycles for urban use to the existing models of full suspension mountain bikes. With this step the company made a move to becoming a full-range bicycle manufacturer. (Third Element 2014a.)

Third Element's products are positioned in the premium segment of the electric bicycle market. The premium status is claimed by using quality components and manufacturing in Germany as well as superior appearance and technology with „the aim of giving users the possibility of moving in a modern, stylish and highly efficient way" (Third Element 2014a). With the numerous customer expectations for premium products on the one side, and the high cost for quality components and manufacturing on the other, Third Element often faces the challenge of keeping their products both attractive and profitable.

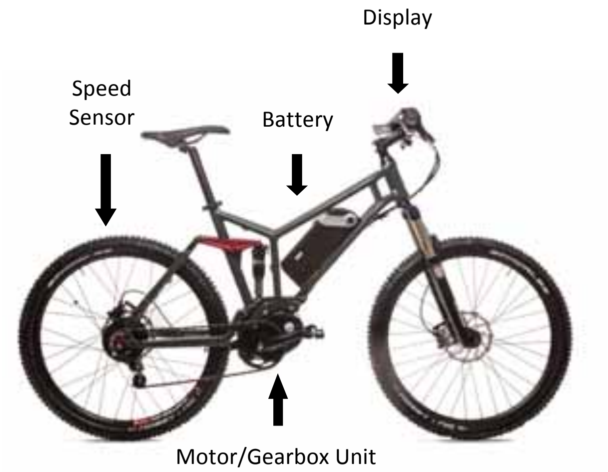

Figure 1. An electric bicycle by Third Element.(Third Element: 2014b)

3 METHOD

This research was carried out as a single company case study for Third Element in Munich, Germany. The proceeding was divided into four steps: First, a data collection on customer feedback was conducted within the case company in order to assess the needs of their customers. Second, a preliminary design was made and presented to the General Manager of Third Element. Third, a mid-term review was held, in which the General Manager added his comments and suggestions to the preliminary design. Last, the authors improved and finalized the design.

3.1 DATA COLLECTION

The Axiomatic Design process starts with the customer domain, which assesses the needs of customers. In order to familiarize with the needs of Third Element's customers, an extensive data collection was conducted within the company. All data used in this research is secondary data from organisational records of Third Element. The records comprise notes from trade fairs and exhibitions, test drive evaluations, emails from retailers and users, internal evaluations and a survey among retailers conducted by a consultant agency. The oldest document taken into account was an employee's note from May 2010 and the newest was a test drive evaluation from November 2013. Based on this material, a total of 440 customer statements were identified, which originated eiter from consumers, business customers or internal evaluations.

Sorting and processing of the data was done manually. Due to the number of customer statements, redundancy, and varying impact on decision-making, a 'sort and combine' approach was taken. This means that statements to the same topic were sought and if suitable, condensed into a functional requirement (FR) or design parameter (DP) as illustrated by the example given in Figure 2.

Id.	Customer statement
49	"Quite a lot of force needs to be applied to the brake levers to generate an acceptable deceleration."
62	"The brakes were still sufficient, although you could feel that they were stressed."
217	"Insufficient brakes."

FR_7: Stop sufficiently
A function that provides sufficient power to stop the vehicle, giving the user a feeling of control and safety.

Figure 2. Combination of multiple customer statements into one FR.

3.2 DESIGN

Based on the 440 customer statements collected and the expertise of the General Manager, FRs and DPs were formulated. The structure of the modules follows the company's modular framework for electric bicycles (Third Element: 2012b).

3.2.1 TOP-LEVEL FRS AND DPS

Table 1. Top-level parameters for electric bicycle design.

Index	FR	DP
1	Provide basic structure	Frame assembly
2	Allow movement	Wheel set
3	Drive electrically	Electric drive assembly
4	Drive mechanically	Mechanical drive assembly
5	Interact with user	Human interaction components
6	Suit individual user needs	Flexible accessories packages
7	Stop sufficiently	Quality hydraulic disc brakes
8	Allow use in darkness	Lighting package, frame mount

The design equation is given by

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & X & 0 & 0 & 0 \\ X & 0 & 0 & 0 & 0 & X & 0 & 0 \\ X & 0 & X & 0 & 0 & 0 & X & 0 \\ X & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \\ DP_8 \end{Bmatrix}. \quad (1)$$

3.2.2 DECOMPOSITION OF FR_1 AND DP_1

Table 2. Decomposed parameters for frame design.

Index	FR	DP
11	Provide strong support	Frame composed of closed-section aluminium members
12	Smooth surface	Quality weld seams
13	Frame shock absorption	Suspension front fork
14	Unique design	Double top-tube
15	Easy to clean	Wet paint

The design equation is given by

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \\ FR_{15} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \\ DP_{15} \end{Bmatrix}. \quad (2)$$

3.2.3 DECOMPOSITION OF FR_2 AND DP_2

Table 3. Decomposed parameters for wheels design.

Index	**FR**	**DP**
21	High tyre shock absorption	Large diameter tyres
22	Low rolling resistance	Low friction profile

The design equation is given by

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix}. \quad (3)$$

3.2.4 DECOMPOSITION OF FR_3 AND DP_3

Table 4. Decomposed parameters for electrical drive design.

Index	**FR**	**DP**
31	Propulsion	Motor-/gearbox unit with integrated controller
32	Interaction with electrical drive	High value display
33	Speed metering	Speed sensor, spoke magnet based method
34	Innovative charging	Inductive charging system
35	Control of the electric drive	Controller software
36	Assist during walking	Walking assist
37	Good gearshift performance	Gear sensor
38	Sufficient range	Lithium-ion battery

The design equation is given by

$$\begin{Bmatrix} FR_{31} \\ FR_{32} \\ FR_{33} \\ FR_{34} \\ FR_{35} \\ FR_{36} \\ FR_{37} \\ FR_{38} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & X & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ X & X & 0 & 0 & X & X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \\ DP_{34} \\ DP_{35} \\ DP_{36} \\ DP_{37} \\ DP_{38} \end{Bmatrix}. \quad (4)$$

FR_{32} and DP_{32} may be further decomposed as:

Table 5. Third level display design.

Index	FR	DP
321	Intuitive operation	Graphical user interface (GUI)
322	Good visibility	High contrast screen
323	Sufficient functionality	3 drive modes

The design equation is given by

$$\begin{Bmatrix} FR_{321} \\ FR_{322} \\ FR_{323} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{321} \\ DP_{322} \\ DP_{323} \end{Bmatrix} \qquad (9)$$

FR_{36} and DP_{36} may be further decomposed as:

Table 6. Third level walking assist design.

Index	FR	DP
361	Software function	5 km/h limiter software module
362	User control	On/off button

The design equation is given by

$$\begin{Bmatrix} FR_{361} \\ FR_{362} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{361} \\ DP_{362} \end{Bmatrix}. \qquad (5)$$

3.2.5 Decomposition of FR_4 and DP_4

Table 7. Decomposed parameters for mechanical drive design.

Index	FR	DP
41	Control application of power	Derailleur gears
42	Compatibility with electric drive	Single speed crank set

The design equation is given by

$$\begin{Bmatrix} FR_{41} \\ FR_{42} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{41} \\ DP_{42} \end{Bmatrix}. \qquad (6)$$

3.2.6 Decomposition of FR_5 and DP_5

Table 8. Decomposed parameters for human interface design.

Index	FR	DP
51	Saddle shock absorption	Comfortable saddle
52	Steering control	Quality grips

The design equation is given by

$$\begin{Bmatrix} FR_{51} \\ FR_{52} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_{51} \\ DP_{52} \end{Bmatrix}. \qquad (7)$$

3.2.7 Decomposition of FR_6 and DP_6

Table 9. Decomposed parameters for accessories design.

Index	FR	DP
61	Protection from dirt	Quality mudguards without reflector mount
62	Protection from oil and grease	Quality chain protection
63	Goods transport capability	Carrier without light mount
64	Multi-media functions	Mobile phone interface

The design equation is given by

$$\begin{Bmatrix} FR_{61} \\ FR_{62} \\ FR_{63} \\ FR_{64} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{61} \\ DP_{62} \\ DP_{63} \\ DP_{64} \end{Bmatrix}. \qquad (8)$$

3.3 Constraints

Table 10. Constraints table.

Index	Constraint	Impacts FR							
		1	2	3	4	5	6	7	8
1	Cost	-	-	-	-	-	-	-	-
2	Weight	-	-	-	-	-	-	-	-
3	Creates fun	-		-	-	-	-		
4	Easy to use	-	-	-	-	-	-	-	-
5	Legal requirements	-	-	-	-			-	-

Table 10 shows the constraints of the design and was adopted from the example of the mechanical design of a chemical-mechanical-planarization machine as described by Suh (2001: 407-440). The constraints are shown on the left side, while the FRs, which may be affected by a constraint are shown on the right side. For example with C_3 ("Creates Fun"), numerous customer statements were found either praising or criticizing the structural behaviour (FR_1) of a bike, while no comments were found regarding FR_2. Therefore, it can be assumed that for the goal of creating a joyful user experience, attention to the emotional perception of FR_1 has to be paid, while with FR_2 it would be sufficient to concentrate on technical requirements only.

The constraints should be understood as an underlying element, which affect all corresponding design decisions. Furthermore it is suggested to create more constraint tables, one for each design level. While Table 10 shows the constraints for the top-level FRs, similar tables should be created for each step in the decomposition process to add more detail to the design.

3.4 Design matrix

Mapping in between the functional domain and the physical domain resulted in the design matrix shown in Figure 3. The layout of the design matrix used in this research is a combination of the matrices used by Carnevalli, Miguel and Calarge, (2010: 6) as well as Suh (2001: 282-283). The FRs, as formulated in the previous sections, can be found in rows while the DPs are shown in columns. An “X” at the intersection of a FR and a DP indicates dependence in between both elements, while an empty cell means that there is no dependence. Cells on the diagonal are highlighted in grey, making it easier to see that the result is a lower triangular matrix, which corresponds to a decoupled design. Thus, the design is not coupled but there are interdependencies. For example, FR_{21} (high tyre shock absorption) is not only affected by DP_{21} (large diameter tyres) but also by DP_{11} (frame composed of closed-section aluminium members) and DP_{13} (suspension front fork), because frame and fork dimension have to fit together with tyre dimensions.

FRs	DPs																											
	1					2		3											4		5		6				7	8
	1	2	3	4	5	1	2	1	2			3	4	5	6		7	8	1	2	1	2	1	2	3	4		
									1	2	3				1	2												
1.1	x																											
1.2		x																										
1.3			x																									
1.4				x																								
1.5					x																							
2.1	x		x			x																						
2.2							x																					
3.1	x							x																				
3.2.1									x																			
3.2.2									x	x																		
3.2.3											x																	
3.3												x																
3.4	x												x															
3.5												x		x														
3.6.1												x		x	x													
3.6.2												x		x		x												
3.7																	x											
3.8	x						x	x	x		x			x				x										
4.1								x									x		x									
4.2								x												x								
5.1						x															x							
5.2																						x						
6.1	x		x																				x					
6.2																								x				
6.3																									x			
6.4																										x		
7	x		x					x																			x	
8			x																									x

Figure 3. Design Matrix.

3.5 SUGGESTIONS FOR PVS

Following the mapping in between the functional and the physical domain, the authors also investigated the process domain. While it was not possible to formulate all process variables (PVs) at the time this research was conducted, suggestions for the realization of those DPs were made, which had enough information available:

- PVs for DP_{12} (quality weld seams) may comprise values related to the welding process such as welding method, type of filler material and degrees of freedom during the welding process (Weman 2012 :210).
- DP_{15} (wet paint) may be further defined by variables relevant to the tasks done in the paint shop, for example the number of layers applied.
- DP_{21} (large diameter tyres) and DP_{22} (low friction profile) may result either from automated or manual (‘hand-made’) tyre manufacturing processes.
- Since DP_6 (flexible accessories packages) and all of its sub-components are optional parts, it is advisable to define inventory control parameters for the manufacturing process, such as safety stock to meet fluctuations in demand (Hopp and Spearman 2011: 73).
- With DP_7 (quality hydraulic disc brakes) it can be relevant to choose either manufacturing in Germany or manufacturing in other parts of the world.

3.6 EXAMPLE OF CALCULATING THE INFORMATION CONTENT

With FR_{13} (suspension front fork) the requirement for a “reasonable amount of travel” (cf. 3.2.2) was discussed. With this wording, it should be questioned what is ‘reasonable’ and how can the requirement be quantified? The solution can be found in the calculation of the information content.

Assumed that the majority of customers considers a travel of up to 100 mm as reasonable, the system range for this FR is 0-100 mm. Further it is assumed that Third Element wanted to investigate two design options: Fork 1 with 80 mm maximum travel and fork 2 with 100 mm maximum travel.

In case of fork 1 the design range overlaps with the system range by 80 %, which means that the possibility $P_{13\ (\text{Fork 1})}$ to meet the requirement is 0.8. Using formula (4), the information content of FR_{13} equals to

$$I_{13\ (\text{Fork 1})} = \log_2 \frac{1}{0.8} = 0.32. \qquad (9)$$

In case of fork 2, $P_{13\ (\text{Fork 2})} = 1$ and the information content is

$$I_{13\ (\text{Fork 2})} = \log_2 \frac{1}{1} = 0. \qquad (10)$$

Thus, the information content of fork 1 is higher than that of fork 2, the latter should be become part of the design if this would not violate any constraints.

Calculations of this kind should be done for each element of a design, and the overall information content of the design as a whole should be calculated as well.

4 RESULTS

4.1 The Axiomatic Design based Third Element electric bicycle

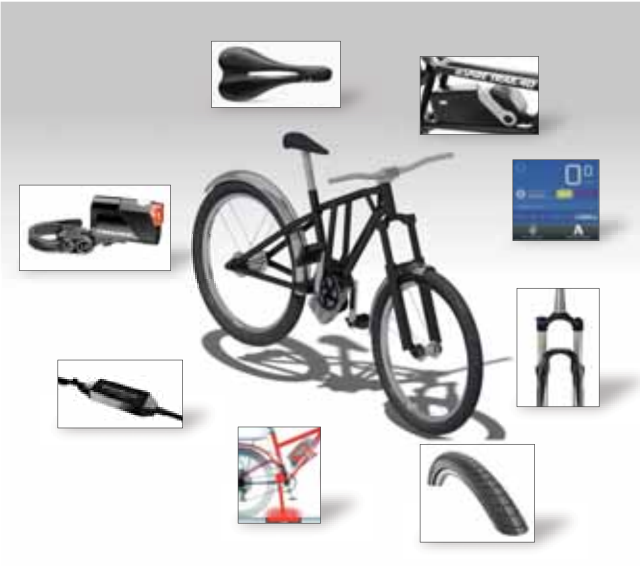

Figure 4. Proposed concept.(Agentura repro 2014, Ralf Bohle 2014, Electric Cyclery 2014, Selle Italia 2014, SEW-EURODRIVE 2012, SRAM 2014, Third Element 2012a, Third Element 2014c, Trelock 2014)

A concept for a novel electric bicycle was created that is defined by the following main characteristics:

- An uniquely shaped frame which clearly distinguishes the vehicle from competitor's products,
- a combination of an effective front suspension, comfortable saddle and shock absorbing tyres which provides riding comfort, even though the frame is a rigid construction,
- a gear sensor which makes shifting of gears easily possible even under load conditions, turning a major weakness of electric bicycles into an advantage,
- reduced complexity and the possibility for increased customization by a fully modular arrangement of components and component groups, especially concerning the speed detection system and accessories,
- an innovative and reliable charging system which makes charging of the battery easy and convenient and,
- additional multi-media functions for better human-machine interaction, thereby improving key functionalities such as driving range as well.

The proposed concept further comprises a rigid frame which ensures stability and gives the user a feeling of control and safety, a graphical display providing exactly defined functionality, a speed sensor without interdependencies to other component groups, and intelligent controller software which further improves a variety of performance factors.

All of the above-mentioned characteristics are based on original customer feedback as well as professional expertise, which make the design likely to please the user. The technical realization exhibits reduced dependencies and complexity due to the use of the Axiomatic Design mapping principles. Due to the constraints, which have been paid attention to, legal requirements are still met and price and weight are kept within reasonable limits. Overall, these factors contribute to a design that is likely to be superior to solutions not based on Axiomatic Design.

4.2 Opportunities and limitations of Axiomatic Design with this case

All in all, Axiomatic Design showed to be of advantage to electric bicycle development at Third Element.

The application of Axiomatic Design to the case of Third Element's electric bicycle development showed to have substantial opportunities. In his feedback on the results of this study, Third Element's General Manager (2014) pointed out that "Axiomatic Design helps to analyse the capabilities and visualizes the dependencies of the single components" and that "many mistakes can be shown at an early stadium, so time can be saved without getting these results too late in a more advanced stage". He added that fewer mistakes will be done and problematic dependencies can be avoided, especially when teams work together at different departments. Further the General Manger agreed with the starting point of the process, which is user feedback, or – in case of products or components that are completely new to the market – a mix of personal experience, market research, or pilot studies. (General Manager, Third Element (2014.)

Limitations with the application of Axiomatic Design to this case exist, but are minor in their impact and can be dealt with. One limitation may be seen in the workload that comes with the quantitative assessment of the Information Axiom, which appears to be a well-known problem in research on complexity. Already in the 1990s, Calinescu, Efstathiou, Schirn and Bermejo (1998: 724) warned that the task of measuring complexity is time-consuming, requires a lot of involvement and might not be carried out thoroughly. Therefore, an exact calculation of the information content might exceed the resources of small companies like Third Element. As a work-around, the Information Axiom could be assessed in a qualitative way, as done by the authors. Another difficulty comes with mapping from the customer domain to the functional domain. This step can be time-consuming if the number of customer statements is large. Additionally, the mapping process from CAs to FRs is not of the analytical kind as with the other domains, so that designers are asked to come up with their own ideas of defining FRs in the best possible way. This freedom of choice of FRs leaves room for criticism. For example Mann (2002: 4) pointed out that – despite the arguments put forth by users of Axiomatic Design – a large number of freezers with vertically hinged doors had been sold, concluding that the FRs chosen for that design could not be the requirements most important to customers.

5 CONCLUSION

The collection and review of 440 individual customer statements marked the starting point for this case study. Based on the dataset, Axiomatic Design was applied to electric bicycle development at Third Element. This comprised the definition of FRs and DPs, their analytical mapping in order to create the design matrix, the formulation of PVs and constraints, as well as the discussion of the information content. As the result, a novel electric bicycle concept was presented.

Concerning the question on how an Axiomatic Design based electric bicycle is specified, it can be answered that a vehicle design following this approach is defined by six main characteristics organised in a decoupled design with reduced complexity. The main characteristics comprise a uniquely shaped frame, which distinguishes the vehicle from competitor's products, while a combination of comfort elements ensure pleasant riding capabilities. Further the use of a gearshift sensor and the possibility for an inductive charging system are innovative features, which pave the way to the future. In addition to that, flexible accessory packages and additional multi-media functions broaden the customer base and contribute to better human-machine interaction. The Independence Axiom is taken into account by a fully modular arrangement of components, leading to the additional benefit of numerous possibilities for customization. The Independence Axiom has also helped to resolve existing and future coupling problems. The qualitative use of the Information Axiom has led to overall reduced complexity.

The question on the opportunities and limitations of Axiomatic Design with this case was addressed by the collection of feedback from the case company as well as the critical reflection of the design process. It can be concluded that Axiomatic Design bears substantial advantages to electric bicycle development, especially towards two aspects: First, Axiomatic Design helps to translate customer requirements into product specifications by providing an all-encompassing design framework. Second, analytical methods within this framework visualize dependencies in between components of the design. Both aspects together support designers in creating products that meet customer expectations better and require less rework during the development process. Difficulties occurred with the processing of customer statements and the quantitative application of the Information Axiom. With customer statements it was challenging to manually translate them into FRs due to their large number. The quantitative assessment of the information axiom was difficult to realize due to the in-depth system knowledge required on the one hand, and limited resources on the other hand.

Taking into account the challenges identified with mapping from the customer domain to the functional domain, future research may investigate how to combine Axiomatic Design with methods that enable effective processing of large amounts of customer data. If this was possible, the result would contribute towards an even broader framework for analytical product and service design.

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