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Design for excellence to explore complex product service systems: A case study

Geir Ringen[a]*, Kristin L. Landsem[a], Halvor Holtskog[a,]

[a]*NTNU Norwegian University of Science and Technology, Richard Birkelandsvei 2b, Trondheim, 7491, Norway.*

* Corresponding author. Tel.: +47 41 67 98 34. *E-mail address:* geir.ringen@ntnu.no

Abstract

Complexity in new product development is claimed to continuously increase, causing challenges that require new and cross-disciplinary solutions. There are at least three major forces causing upheaval in the way we are designing, engineering, producing and using/reusing products: 1) achieving the sustainability goals, 2) availability of digital technology at ever lower costs and 3) personalization and customization of products. This study seeks to investigate future solutions for the street light infrastructure based on Design for X approaches – and enablers and barriers for innovation in the stakeholder network. Light poles are traditionally been an enabler for illuminating the road in a static manner, whilst such structures in the future are predicted to host a multitude of technologies for serving a broader array of functionality. Examples of added value functionality are; crash management, smart control systems for energy saving, ease of maintenance, sensor-service system that provides stakeholders with real time information about the road environment, sensor technology for enabling autonomous driving etc. To explore this functionality, a Design for Excellence product development methodology is used to structure the gathered information from multiple sources. Both a qualitative and quantitative methodologies are used, where the former is conducted by interviewing value chain stakeholders for the complete road light infrastructure domain in one region and the latter is done by a structured questionnaire. The common ground for both approaches is Design for excellence which is regarded as a systematic way of designing products to optimize total benefits over the whole product life span. Findings from this study suggest that safety and reliability are the two most important requirements when designing a light pole for future demands.

Keywords: Material substitution; Product-service system; Desig for excellence

1. Introduction

The first city in the world with electrical street lighting was Newcastle in 1879. Over the last decades different luminaires, in particularly LED, and different light control systems have experienced a great development resulting in more efficient energy usage [1]. It is estimated that 20% of the world's energy is used for lighting, so there is a considerable potential to be exploited when it comes to energy reduction [2]. Lately, new technology such as IoT and AI have been implemented into these systems to further increase the efficiency. There are already some project utilizing smart road lighting infrastructure. In Copenhagen, The Renewal Project has changed 6800 light poles, upgrading 300 km with new lights to meet the future requirement concerning both CO2 emissions and being a smarter city. They have estimated the energy savings to be nearly 55.7%, and it is estimated to save 3223 tons of CO2 each year. Nevertheless, they believe that the greatest investment is in the new sensor technology, connecting Copenhagen through a wireless network integrated into the light infrastructure [3]. In Oslo, a similar project aims at replacing old mercury luminaire with LED, which evolved to changing 25000 points, integrating wireless network sensors in all of the luminaires [4]. Such an upgrade is complying with several of UNs sustainable development goals which aim for building resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation while simultaneously combat climate changes. With faster

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development, the control system and luminaire are getting more and more complex. Increasing complexity may reduce component lifetime and require new ways to assemble, operate and maintain the system [5].

This study aims at understanding potential enablers and barriers for innovation within the development, use and recycling of road lighting infrastructure. It is foreseen a huge transition in this field of application, not only due to energy efficiency, but also its proximity to people and traffic gives rise to many ideas for information exchange, communication, safety, traffic control etc. The investigation starts with identifying stakeholders, interviewing stakeholders about important requirements, needs and wants, and surveying and quantifying these features by getting feedback from a broader market perspective. Design for excellence is the selected approach for analyzing inherent and potential complexity of road light systems. The main research question is: how can the method DfX be used to map important design features and quantify them into enabling and disabling factors for system complexity?

2. Method

This study is carried out as a case study due to the fact that limited knowledge about the phenomena was initially to be found. A case study is one way of understanding complex social phenomena, used in many situations to contribute to our knowledge of groups, organizations and related phenomena within a real life context [6]. As Harrison [7] put it, case study research is of particular value where the theory base is comparatively weak and the environment under study is uncertain. This approach also allows for a variety of evidence extracted by a multitude of techniques and from many sources of information. Here, a brief literature review is conducted to get an overview of the particular application to be investigated, a stakeholder analysis with subsequent semi-structured interviews is done, and a broader picture of market requirements is outlined through a survey. Several sources of information pointing to the same conclusion will naturally strengthen the research validity.

The brief literature review of the application at hand includes systematic searches in titles and abstract in Oria and Compendix on phrases like "Road and street lighting", "Light poles", "Traffic safety", "Aluminum light poles" and "Wireless network sensors". Responses from the search were categorized into scientific articles, thesis, and popular science, and summarized according design for excellence principles. Stakeholders to the application were mapped by snowballing effects, adding actors based on new information from the eco-system. Semi-structured interviews were conducted with key actors in the network, a method suitable to explore the complexity and in-process nature of meanings and interpretations [8]. in total 19 people from 10 different actors were interviewed by a combination of face-to-face, phone and e-mail communication. Before the interviews were conducted an e-mail was sent out to create a common understanding of the project and to prepare the respondent on what kind of information that was of interest. The interviews were not fully transcribed at this stage of the study, but thorough summaries are made.

To depict a broader overview than potentially given by the particular value network through interviews, a survey was conducted and distributed through industry specific channels. This was done to see whether the more qualitative findings were in line with the industry they belong to. The respondents were asked to rate a set of features based on importance on a nine-point Likert scale. 31 companies completed this survey, comprising actors such as suppliers, designers, consultants, municipalities, grid operators, entrepreneurs, and manufacturers.

2.1. Case: Road light system

The case study investigates a light pole system for traffic safety and its inherent complexity as enablers or barriers to further innovation. Such a system contains four major building blocks, the pole itself, the foundation, power supply and the light. The pole is designed based on the requirements for wind and dead loads, height and terrain gradients, speed limit and crash-worthiness. Especially the latter is an important criterion, which are separate into the three classification; high energy absorbing (HE), low energy absorbing (LE) and non-energy absorbing (NE). Typical material selections for the poles are steel, wood, concrete and aluminium, where steel is the dominating material in all three categories. There are three types of foundation, direct embedment pole foundations, drop pipes foundation and footplate foundation. These can be made of either concrete or steel, applying to separate standards. Each light pole and location are dependent on a power supply, either by a trench or hanging cables. Typically, every 300-500 meter a power supply cabinet is located, transforming voltage down to 230/400 V, and distributing it to a number of adjacent poles. The luminaire is defined as an apparatus which distributes, filters or transform the light from one or more lamps [9]. The lighting source is normally made of sodium pressure, metal halide with a ceramic burner or LED. There are also other sources, but they are less common. Which lighting class that should be used depends on speed limits and average traffic frequency. The luminaire should be dimmable in periods when there is less need for lighting, unless an LCA shows that it is less favorable to install a dimmable construction. There are different kinds of lighting control systems, such as a timer, photocell, on/off button and night reduction to mention some, controlled by systems like voltage manipulation, integrated dimming module, a dynamic controlling module, and activity based. Normally, poles and supply cabinets have a lifespan of 30 years, cables have 40 years, and control mechanisms and electrical parts have 20 years. If the luminaire has a magnetic reactor, the capacitor has a lifespan of only eight years. Sodium pressure is built to last 24 000 hours, metal halide with ceramic burner has 12 000 hours and LED are designed to last 50 000 hours [10].

3. Results

3.1. Theory and literature review

Within the domain of product development, complexity is claimed to continuously increase, causing challenges that require new and cross-disciplinary solutions [11, 12]. There are at least three major forces causing upheaval in the way we are designing, engineering, producing and using/reusing products: (i) the pivot of consumers, government and eventually industry towards sustainability goals as mandatory shift for the future of our civilizations (ii) the unprecedent availability of digital technology at ever lower costs, notably sensors, computing power, connectivity and algorithms, and (iii) personalization and customization of products define new standards for how systems can handle increasing number of variations under strict time constraints. These forces introduce a disruption into how we will do innovations and product development in the future. Thus, these trends and shifts will affect all actors in value network or value chain with ambitions to compete on the global stage, introducing unknown unknowns and interrelated factors that cannot merely be solved by existing rules, systems and processes. As Nason puts it [13]: "if you manage complex things as if they are merely complicated, you're likely to be setting your company up for failure". To further delve into how this complexity can be managed the theory of Design for Excellence, or DfX, is selected as the foundation for this study.

DfX is regarded as a systematic way of designing products to optimize the total benefits over the whole product lifespan [14]. Originally it was provide guidance and an effective way to allocate resources towards solving the most important market demand [15]. Now, the DfX can be a useful tool in understanding and improving the entire product lifecycle by including the phases of use, reuse, recycle and disposal. The X in DfX can hold many different values, and the X's reflects an identification on all aspects related to expectations and demands to a product. This is a bottom-up process, where individual wants, needs and requirements are put together to shape the product more comprehensively [16]. Holt & Barnes [17] divide DfX into two subgroups – either choose X's according to the product's virtues or its life phase. To simplify the DfX approach, all stakeholders should preferably be identified so that the X's can be categorized accordly.

Design for order, DfO, is not the foremost mentioned objective in the general design literature. For road light poles builders and entrepreneurs order depending on which road or street that needs lighting according to road classification. Due to many laws and regulations concerning traffic safety the relatively standardized light poles are often ordered to optimize price and delivery time. If the purchaser is the municipality, it is a road lighting norm that needs to be followed when ordering light poles. These norms describe which poles to use to make a more comprehensive design impression of the township. Typical stakeholders for this product life phase are consultants, builders, suppliers, and entrepreneurs. Requirements for safety and lumen applied to the road are standardized features, and today only a few suppliers are pre-certified to supply such solutions. Thus, properties such as design space, smart functionality, connectiveness, etc are not predominant features when negotiating price for light poles.

Design for assembly, DfA, is a process aiming at designing products that enables assembly as well as dis-assembly, where material selection, component design, joining methods etc are important criteria for fulfilling the objectives of DfA. Designs that focus on assembly is also more likely to avoid redesigns. Edwards suggested to make components symmetrical, standardized, with few materials, with few high precision fits, without sharp corners as guidelines to ease the assembly procedure [18]. Manufacturers of light poles, entrepreneurs, and electrical contractors are found to be the primary stakeholders in this product life phase. The cost of road lighting is divided into construction and operation/maintenance, where the former accounts for about 33% of total cost whereas the latter 67%. It is assumed that todays relatively standardized light poles only 10% of the construction costs are related to assembly on-site.

Design for Usage, DfU, is about how effectively, efficiently and satisfactorily a user can interact with a product. A product should have intuitive design, low operations cost and thereby reduce error frequency and severity to a minimum. For light pole systems the buyer and user is traditionally the same actor, but can be exceptions where electrical contractors or grid operators are operators. Road lighting is primarily motivated by road safety, but traffic management, well-being, and aesthetics are positive benefits by lighting up streets and roads. The pole itself is mainly used to hold the luminaire, but in some areas where the speed limit is low, it is also used to hang-on different kind of signs, commercials or decorative objects. With the increasing focus on smart cities, IoT and AI, the traditional Light poles are regarded to have a potential for exploiting other applications than just illuminating roads and streets.

Design for Maintenance, DfM, assumes the output to a product-service-system that will be relatively easy to maintain at low cost throughout its life-cycle [19]. When designing a product for maintenance, it is important to build-in features that detect failures as early as possible for complying to the state of predictive maintenance. Moreover, ease of repair in terms of replacing broken parts without interrupting critical functions, ease of access to minimize repair time and minimize the need for special tools and complicated operations all contribute towards DfM [19]. Today, the maintenance is mainly done by an electrical contractor since most maintenance need is related to electrical failure modes and not the pole itself. Lifts, winches, wedges and climbing are all possible solution for accessing the light pole – depending on type of repair and maintenance.

Design for Recycling, DfR, is becoming more and more a supplier responsible, regardless of who is responsible for taking care of the disposal, for recovering products at end of life [20]. Products should be disassembly-friendly, consist of materials possible to recycle and few parts, and high-value materials that are easy to separate. Stakeholders to this stage are the society, production sites, recycling stations, and the entrepreneurs that dismount the light poles. With the increasing trend of being more environmentally friendly, it became clear that the stakeholders saw value in having a functioning recycling plan for the product from cradle-to-grave.

3.2. Interviews and survey

The lifespan of a light pole, and similar infrastructure, can consist of up to eleven phases, but 5-9 phases should be appropriate to analyze the overall complexity [18]. This study prioritizes the phases from 7-11, emphasizing ordering, assembly, usage, maintenance and recycling. Thus, the project planning phases and the manufacturing phase are sorted out of the equation. Through the interviews, based on snowballing effects, the stakeholder matrix for these phases is shown in Table 1. In total 18 stakeholders are identified, ranging from Nature, Society and to directly involved contractual formal actors.

Table 1: Stakeholder analysis.

DfX	Stakeholders				
Order-ing	State, County and Muni-cipality	Consul-tants	Manu-facturers	Entre-preneurs	Grid operators
As-sembly	Entre-preneurs	Electrical contractor	Manu-facturers	Equipment owners	Grid operators
Usage	Vulner-able road users	Light control	Nature and wildlife	Grid operators	Equip-ment owners, system mainten-ance
Mainten-ance	Electrical contractor	Certifying unit	Manu-facturers	Operators	
Re-cycling	Electrical contractor	Society	Manu-facturers	Recycling units	

The interviewees are asked questions with regards to map requirements, needs and wants for each phase. Table 2 depicts the summary of prioritized features made by the respondents, giving nine distinct features that most probably will satisfy the majority of stakeholders.

To verify and value, and potentially refine and remodel, the answers given through semi-structured interviews, a survey was distributed to an industry-wide network. this network consists of manufacturers, suppliers, customers, equipment owners, maintenance operators, grid operators and electrical contractors. The same features as identified through interviews were presented as statements in the survey, giving the respondents a choice of grading the importance of these features according to the DfX phases. The average survey score for each feature is given in the right-hand column in Table 2.

3.3. Explanation and discussion

The feature More variation was considered the least important of all virtues. Analyzing the comments given in the questionnaire, several of the participants claim that it already exists a great variety of design. However, they mentioned that it is important to have a clean design which fits the design of the luminaire aesthetically. Some wrote that changing the design of the pole could potentially force a change in the luminaire design. Price is ranked as the third most important criteria, having only a few comments attached saying that the life-time cost should be given more attention than investment cost in project evaluations. However, some commented that the market will always determine the price, so if the pole is getting remarkably better people are most likely willing to pay for it. Safety was ranked as the most important virtue in total, not only important for the road users and to comply to regulations and laws, but the fact that safety does function as a selling argument.

Table 2: Design features by DfX phases.

Features	DfO	DfA	DfU	DfM	DfR	Average score from survey
More variation	X					1
Lower price	X	X				7
Improved safety			X			9
More information			X			6
Increased reliability			X	X		8
More add-on functionality			X			4
Improved access			X	X		2
Improved recycling					X	3
Improved environment					X	5

Even though sensors and connectivity are enabling technologies for retrieving information from the road lighting systems, and potentially communicate two-ways with the system, this feature is not rated more than medio in this study. Some respondents argued that energy usage, added censors and cables, and monitoring may cause more resource usage than value. However, maintenance and light control by censors are emphasized as interesting features. Reliability of the system plays a significant role for municipalities and equipment owners due to cost and up-time responsibility. The interest for add-on functionality, for increased flexibility of the system, was rated below average. Several stakeholders wrote that it is strict regulation for what the poles can be applied to as extensions to their main purpose. The feature Access is rated low due to the fact that the respondents claim existing solutions for accessing the poles are satisfactory. Due to recycling and the environment material selection should get more attention.

Some comment that environmental concerns are almost absent when choosing pole designs today.

3.4. Short summary of discussion

A survey is answered by a number of stakeholders due to DfX features for road lightening systems. Substituting existing solutions should at least improve safety and reliability, and reduce costs. Moreover, sustainability, added functionality and smartness are, to some extent surprisingly, ranked medium to low by the panel.

4. Conclusion

This study seeks to theoretically answer how DfX as a method can be suitable to map design features based on both qualitative and quantitative methods – applied to case study for road lighting systems. Interviews from actors in the value chain revealed a set of design features of importance related to the DfX-stages, and in-depth knowledge about existing requirements and future opportunities. Next, these insights formed the basis for a questionnaire, being distributed to an industry-wide network, to rate and quantify the design features. These two applied methods, in combination, provide a thorough overview of what actors in the existing value chains claim as enablers and barriers for further innovation. However, the results seem to support a relatively conservative attitude among the stakeholders, rating reliability, safety and price as the most important design criteria and variation, flexibility and sustainability accordingly lower on the ordinal scale. We claim that DfX as a method is an appropriate approach for mapping important requirements, needs and wants, but less appropriate as a tool for guide innovation in an era of rapid technology development – given the actors, value chains and networks subject to this study.

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