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Design for green lean building module production - Case study

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Abstract

With an increasing societal need for temporary buildings, while construction industry faces resource and time efficiency challenges, factory assembly of modular buildings can be a solution. This case study at a start-up company uses experiences from assembly system design and eco-design literature to propose green lean design principles to be used in the design and development of building modules and their assembly stations. The eco-design strategy wheel is used as a basis and adapted for the assessment of green and lean building manufacturing.

Peer-review under responsibility of the scientific committee of the 8th Swedish Production Symposium.

Keywords: modular building production; green lean; eco-design

1. Introduction

This paper presents a case study with a start-up company producing building modules while aiming for lean and sustainable production. Society faces multiple challenges to provide additional buildings for housing, schools, kindergarten etc. Up to a third of the demand is of a temporary character, where building permits expire within 15 years [1, 2]. Policy makers meanwhile acknowledge a demand for workplaces, providing labour opportunities for applicants with low educational levels or new immigrants, so-called “simple jobs” [3, 4].

The business idea of the researched company, Husmuttern AB, is to provide low price standardised modular houses for temporary use and “simple jobs” [5]. Operations are standardised to facilitate simple, lean and sustainable manufacturing [6]. In the assembly operations, social sustainability aspects such as health, safety and ergonomics are

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crucial. A previous study of the company business concepts concluded that the concept needs further environmental analysis of the design of product and operation assessed from a life cycle perspective [5]. It also identified renting out the production equipment as a product service system, in a factory in a box concept [7] as opportunity for further development.

Green lean (GL) is a management approach where lean management and green management strategies are combined. In lean and economic sustainability management, companies can develop their own company specific lean principles in a Company-X production system (XPS) [8, 9]. In green management strategy, eco-design strategies are applied for products, services and production processes [10]. In GL, sustainability aspects (ecologic, economic and social sustainability including occupational health and safety) are integrated in a holistic lean management [9, 11]. Tools are chosen in line with general GL and company principles. In architectural engineering and construction industry a need for further research exists regarding the integration of lean and green management and information systems [12], such as application of tools for decision support regarding greener constructions.

The aim of this paper is to evaluate a green and lean design approach regarding its purpose to reduce environmental impacts for product, services and production as a whole, while not compromising economic and social functionality and sustainability. The results from using the eco-design strategy wheel tool are evaluated and compared to the literature and to lean principles. The research question for the study is:

- How can the eco-design strategy wheel be used as a green lean tool in the early phases to design product and process in modular house production?

In this study, we propose to use the eco-design strategy wheel as a GL tool for life cycle based eco-design. The study is limited to this specific tool and explores the applicability of this ready-to-use tool to support design in achieving for instance material efficiency goals. In particular, the suitability for practitioners with limited competence and available time will be scrutinised. The study does not assess whether Husmuttern is fully lean or fully sustainable in design or operation. The contribution is related to findings from a case with simultaneous product and production development supporting GL principles in modular construction production.

2. Theoretical background

In Green Lean, sustainability aspects (ecologic, economic and social sustainability including occupational health and safety) are integrated in a holistic management with sustainable and lean company principles and values [9, 11]. The product, production and end of life should all be in line with the green lean XPS principles and company values. A review of green lean and information management for construction industry [12] found that tool selection needs to consider the maturity of the company. There is a potential synergy in combining green tools, which often focus on design, and lean tools, which often focus on production and delivery. A principal lean tool is Value stream mapping (VSM) focussing on minimising lead time and increasing value to customer. A principal green tool is life cycle assessment (LCA), focussing on minimising environmental impact and improving eco-efficiency [13]. Tools that are green, lean or combined which provide some benefits in both areas and do not jeopardize either goal are considered GL tools. As an example, environmental-VSM is considered a GL tool, although it does not consider all environmental or all lean aspects. The improvement approach system, central both in lean and GL, builds on lean principles and is manifested through tools, methods and standards used in the production system [8]. In GL product development it is important that tools support operative decision making. The lean tools typically should be visual, easy to use, time efficient [12] and support analysis of current and target state [14], but there is no exact definition of what a lean tool is [10]. In Lean production respect for people and continuous improvement are cornerstones together with reduction of waste and resource efficiency. In GL a holistic picture (monozukuri) [11] is emphasised and what is considered as waste goes beyond waste of time. Natural resource efficiency and emission reduction is taken into account in GL.

Especially GL requirements addressing material, energy efficiency and waste may be of importance for environmental sustainability of production equipment [15]. In a study of production equipment design [16] interviewees indicated that the eight most important lean design criteria were that the production equipment assures functionality of the concept, including: 1. Safety of operators, 2. Being flexible& minimizing the waste of tool changes. 3. Error proofing 4. Easy and reliable maintenance, 5. Support one-piece flow, 6. Support short setup time, 7. Being simple to use, 8. Resource efficiency. There are several green tools to use for eco design of products and processes [10]. In detailed studies, LCA is recommended for in depth-analysis of environmental performance [17].

The necessary LCA-data is normally fed back to design when working with existing products and markets [18]. In green-field application however this information is not available in early stages and must be estimated or simplified.

Although lean product development is often associated with set-based-design [10], it is still common also in companies applying Lean management to use a stage gate model in product and process development. The gates are constructed to assure that certain knowledge is achieved at each gate. Eco-design is aiming at improving environmental performance, and involves integrating environmental issues throughout the product/process development stages; (1) Specification of requirements and concept - hot spot analysis using eco-design strategy wheel give ideas on improvement of environmental performance. (2) Prototyping and validation of performance – The solutions from eco-design strategy wheel can be validated by LCA. (3) Detailed design and production trials – all critical parameters are fixed, full LCA data is available. (4) Full production and marketing – environmental management (e.g. Operational control in ISO 14001) and requirements of verified environmental information including environmental product declarations (ISO 14025) is applied on products, processes and services [19]. In eco-design, the availability of information limits the design knowledge in early stages.

Integrating environmental aspects in early stages allows for a more sustainable design of both product and production system. Using a simple tool such as the eco design strategy wheel enables environmental consideration in all design stages, a base for continuous improvements. Such early assessment can then be complemented in later stages by more detailed LCA. In the eco-design process, the eco-design strategy wheel (Fig. 1) can be a time efficient tool, substituting a full /proper LCA in early phases of green field design where data is not available [19] . The eco-design strategy wheel is reconfigured from an approach originally proposed by Brezet for UNEP [20, 21] and includes all life cycle stages in order of significance and information ability. The most important issue is to assure functionality (1) of the product and process and minimise impact during the use phase (2). Then the amount (3) of and choice of material (4) is crucial to address. The final steps are optimising life length (5), optimise production (6), end of life (7) and distribution (8). This tool can be used for products, services and processes although not all questions are applicable for service functions. As the development process continues more of the design that is fixed and only details may be changed although more data can be achieved for a full LCA.

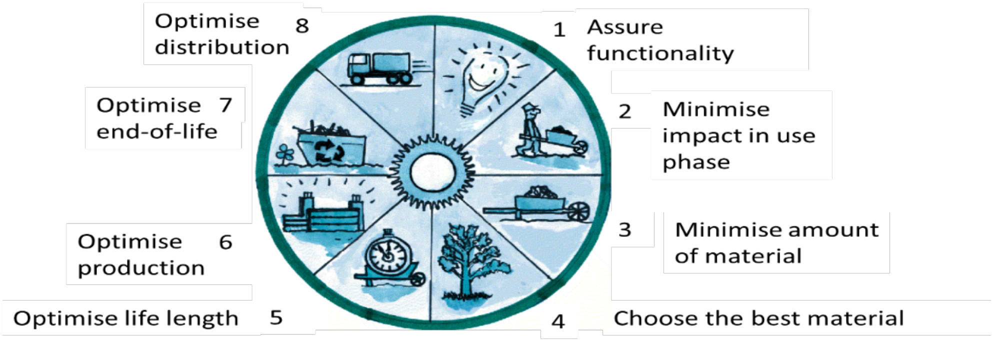

Fig. 1. Eco-design strategy wheel [19] adapted from[21]

The eco design strategy wheel captures all aspects in a life cycle perspective. Thus, introducing the wheel in each design stage helps capture improvement potentials early, with flexibility for instance regarding supplier, materials and energy sourcing. In addition to setting detailed parameters and validating material concepts, the assembly cell prototype needs to be specified and validated. In assembly processes with many manual operations, but few chemicals or energy demanding operations, important environmental sustainability issues include assuring product functionality, quality, material efficiency, and infrastructural energy use [19]. The design of production equipment and infrastructure needs to be in accordance with the demands of the lean production system [22]. Eco-design of equipment using energy and consumables should firstly focus on the use-phase [19]. For production equipment the first four steps in the eco-design strategy wheel are proposed as most important [23].

3. Methods

This paper is part of a more extensive study following the development process of Husmuttern AB. It builds on questions raised in a previous paper where Kurdve and de Goey [5] analysed the business concept and proposed a design driven innovation strategy to drive innovation in the intended sustainability direction. An evaluation of the concept design found opportunities for improvement with regards to environmental sustainability when going forward to prototype and validation stage of the implementation. This paper is limited to development of environmental sustainability, while another paper by Kurdve [6] describes the ongoing prototyping and validation of the social sustainability features, e.g. the creation of safe and simple jobs in the concept.

The theoretical background is used to propose use of a simple eco-design tool as GL tool for identifying environmental improvements. The operations of Husmuttern is therefore evaluated in two steps, each with current state and target state [14]. Firstly, the conceptual design of building modules is evaluated and changes are proposed based on the eco-design strategy wheel used in accordance with [19]. Secondly, based on the eco-design of production equipment [23], the production process of the production is evaluated. Then the results are compared to GL principles to assess if the tool is useful for GL design.

The conceptual design of the wall module was based on a student thesis [24]. Conceptual criteria included low energy use in the final product and mainly use of renewable materials such as wood. However, details of the materials and joining are further developed and changed in the prototyping stage. The conceptual design of the production equipment and the production process were developed in student projects and theses [25, 26]. The production concepts included workers safety, standardisation and efficient transports. The conceptual design going into prototyping is evaluated using the eco-design strategy wheel for physical artefacts like product and production equipment. Finally, the eco-design strategy wheel is evaluated. However, economic feasibility is not assessed.

4. Empirical results

4.1. Concept

The Husmuttern business concept is based on their values: “Be good, Do good, Fair deals”, seen as the baseline of its production system. In these values, the goal of sustainability is brought in. Social and economic sustainability are obvious parts of the business, where the value provided are cheap temporary houses and simple, safe jobs that develop people. This value is thus seen as the product service combination that is provided to the market.

A major challenge from a business and environmental point of view is that temporary buildings have a use-phase of maximum 15 years in one location, while deprecation time of residential buildings is 50 years and of non-industrial buildings 25-33 years. Therefore, capital expenditure and the environmental impact for temporary houses must be less than half compared to that of a permanent building to be competitive and reach the same eco-efficiency. Providing reusable modules is a first step towards this. The building blocks are designed to be reusable and at least last for two lifecycles. The concept is to build the temporary houses of standardised module building blocks that are produced in standardised lean production assembly cells to enhance efficiency. In addition, the concept is designed to be near passive house standard to reach high energy efficiency in a standard outer wall with two-step seal of moisture where the wall thickness and insulation target minimal energy consumption of the house. Ongoing development also considers integrating photovoltaic cells in the roof. The inclusion of the service to offer basic workplaces to develop skills may seem as counteractive to eco-efficiency of the building blocks; prototyping and validation includes validation of ensure economic and ecological efficiency with unskilled personnel.

4.2. Product prototype

The Husmuttern module parts are constructed on frames made of masonite beams with a masonite back and a pine panel sitting on wooden beams screwed to the frame. The wall contains a wind-paper (paper or -non-woven), insulation (stone wool) and a vapour barrier (plastic). All parts are screwed with rust proof screws. The module concept was designed with energy efficiency in mind [24] compared to two other possible wood structure designs. The company has chosen natural standard materials with the expectation that this is a good starting point for continuous development towards lower environmental impact. In the prototyping phase, material suppliers take part to optimize material selection, joining and dimensioning. To evaluate the current state and to propose improvements of environmental impact the eco-design strategy wheel [19] was applied, resulting in a list of future state opportunities.

Table 1. Eco-strategy assessment of house modules: Production cell prototype

Eco strategy	Interpretation	Result current state (concept gate)	Future state
1. Optimise function	Function of building can be met with minimal excess	Modules can be combined as wanted but only standardised blocks	Not all shapes are possible.
	Not needed features avoided	Standard is limiting unnecessary customisation	Not further addressed
	Low price	Standardisation keep cost down, but e.g. cost of pre-cut materials is high	Continuous improvement of efficiency
2. Minimise use-phase impact	Minimise energy use - to passive house standard	Passive house standard	Check that passive house standard is met after prototyping changes.
	Easy to maintain/repair	Possibility exists to exchange single modules.	Yes, but at what cost?
	Possible to refurbish	not addressed yet	It should be easy to change inside surface and paint panels.
3. Minimise material waste	Is spill avoided	Wood is pre-cut to right size	Some materials may become waste, e.g. curved wood.
	Is all parts of modules reusable	All modules are reusable, module parts can be reused/recycled	Possibly difficult to disassemble to reuse beams etc.
	Is all materials recyclable	Wood material may be recyclable to beams. Screws, plastic and insulation is recyclable. Tapes are not.	Need to address efficient disassembly
4. Choose the right materials	Are main materials renewable?	Wood and paper is renewable,	Plastics could be renewable PE, insulation and screws are not renewable.
	Is it possible to use recycled materials?	Masonite, plastic, paper, insulation and steel can have partly recycled origin.	Not sure it is possible to source as recycled.
	Are hazardous materials avoided?	Main material is not hazardous	When choosing supplier: check that the masonite and tapes do not use hazardous materials.
5. Optimise product life	Can product life be above 15 years?	Reusable modules for >15-year life	Needs further evaluation
6. Optimise production	See table 2	See next section - table 2	See next section - table 2
7. Optimise E-O-L	Are materials recyclable	See question 3 above	See question 3 above
8. Optimise distribution	Efficient transports	Transport by truck is optimised for as efficient as possible.	Need to re-check after start of production

4.3. Production prototype

The production concept has been developed in several student projects in parallel with the module design, see figure 2 a. The resulting prototype is shown in fig 2 b. The prototyped cell is based on tool boards on wheels with safety equipment, battery powered tools, and the tools needed for assembly. A communication board with a large video screen is used to show instructions and collect data for quality assurance. Environmental sustainability needs quality assurance and especially fault proofing. Social sustainability it is most important to offer workplaces that train personnel in new assembly skills. To assure this functionality, the prototyping has so far focused on safety and quality fault-proofing (poka-yoke) which is further described in another paper [6]. The eco-design of equipment and operations was assessed with the eco-strategy wheel (table 2) in accordance with Bruch et al. [23]. The manufacturing cell concept has been assessed with regards to functionality, workplace learning as well as health and safety. Experts from Arbetsförmedlingen (Swedish labour office) are taking part in trials and assessing the cell with regards to the aim for safe and learning jobs. At the same trials, tool suppliers and students assess the workplace functionality with regards of producing efficiently with quality.

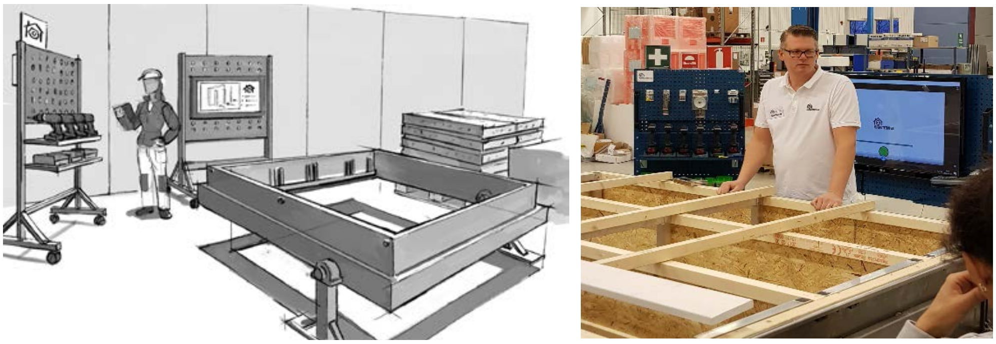

Fig. 2. a) concept design of cell, b) prototype of same cell

Table 2. Eco-strategy assessment of production concept.

Eco strategy	Interpretation	Current state	Future state
1. Optimise function	The workplace should be efficient & flexible for improvement	The cell is reconfigurable	Team improvement system needs to be developed
	Job should train people for steady job in industry/construction	The concept is visual and include training method	Further develop instructions and SWC
	The equipment should be safe also for untrained personnel	Physical safety poka-yokes, avoidance of hazardous equipment/material	Develop systematic poka-yoke system
	The produced product/service should be useful	The training concept produces house modules	Produced houses fit market
2. Minimise use-phase impact	Minimise unnecessary energy use	No pressurised air, only electrical tools Tv-screen and lighting of plant.	Continue work with low standby energy for equipment
	Minimise unnecessary material use	Quality check of mtrl: correct length and width to minimise quality spills	Include supply chain spills in assessment of material efficiency
	Minimise hazardous material use	No hazardous process material is needed according to specification	Check material specification when changing supplier or product.
3. Minimise material waste	Minimise spill	Wood materials are pre-cut, no spill. Small spill on paper, plastics and insulation. Quality spill is apparent.	Reduce risk of defect material.
	recycle spill	Most materials recyclable. No recycling bins are in place, Plastics, metal, wood, paper fractions will occur. Possibly batteries etc.	Standardise packaging material and synchronise to waste fraction standards
4. Choose the right materials	Is equipment made of renewable materials?	No, equipment are mainly of steel.	not applicable
	Is it possible to use recycled materials in equipment?	Yes. Equipment and tools are reused. Steel equipment is recyclable material	Battery and electric tool assessment
	Are hazardous materials avoided?	Yes except for electronics, batteries and fire extinguisher.	Battery and electric tool assessment
5. Optimise product life	Can cell be reconfigurable after project?	Yes, in factory-in-a-box concept	Assess number of uses, maintenance need between projects etc.
6. Optimise production	Can production equipment be reused/recycled at end of project	Yes see 5 and tools are mainly recyclable	See 4 and 5
7. Optimise end-of-life	are tools reusable and recyclable	see 3, 4 & 5 above	see 3, 4 & 5 above
8. Optimise distribution	Efficient transports	Equipment on wheels for easy transportation, heavy steel equipment.	Light weight choices could be assessed

The use-phase assessment of the production cell was assessed with the eco-strategy wheel with regards to design of the cell as in table 2. Energy is only used for the video screen, battery powered tools and lighting. To choose equipment with low stand-by electricity use may be important. Primary material spill is minimised by having pre-cut beams and panels, but there is still a need to consider paper and plastic width optimisation. Also, there are risks getting defect material, such as twisted beams, if they are exposed to humidity. There may also be insulation spill and dust from insulation. Packaging of the incoming material is wood, plastics, and corrugated paper for doors and windows. Recycling bins in the cell for packaging materials are not yet established. Consumables are personal protection equipment and tools, no chemicals or fluids are used. Most materials are renewable and/or recyclable and possible to source from recycled origin.

4.4. Analysis of results

All aspects in the eco strategy wheel should be considered in all development stages, but some aspects are frozen after certain stages. The eco-strategy wheel can be used “as is” for the product, but we propose to introduce “optimise product life” together with “optimise product function” and “minimise environmental impact” in the specification of requirement and concept phase. Optimise product function may be difficult to do for combinations of product service systems and needs more research. Material selection and optimisation can be changed during the prototyping stage and it is recommended to include end-of-life optimisation due to material dependency. Environmental optimisation of production is relevant throughout the process, but is most relevant in prototyping and validation phases. At the end of the prototyping phase, a screening LCA may be used before final sourcing to provide a more thorough analysis. Optimisation of distribution can change in the detailed design, production and marketing phases. Used for production equipment design the tool supported four of eight important lean criteria [16]; Safety of operators, Error proofing, Resource efficiency and Being simple to use. However, the other four: Easy and reliable maintenance, Being flexible, Minimizing the waste of tool changes, Support one-piece flow and Supporting short setup time were not affected by the use of the tool in this case. Due to these results we confirm the eco design strategy wheel as a GL tool in this case.

4.5. Discussion

LCA has been suggested for implementing environmental aspects in GL design. However, simple versions of environmental assessment tools may be used for limited analysis or due to shortage of resources such as time and competence. The Eco design strategy wheel focuses on minimizing environmental impact and improving eco-efficiency and did not explicitly impact flow or lead time, but value for customer were slightly improved. The use of the tool was perceived as easy to use, fairly visual, and quick to deploy, thus, accessible for many roles. It required only limited time and low expertise.

The tool supports operative improvement system and decision making with current and target state being visualized in table 1. Since detailed LCA data around materials may be difficult to find in early phases, the eco-design strategy wheel and green principles can support practitioners to approach environmental goals. The assessment shows that simple rules to avoid hazardous materials and aim for renewable or recyclable material lead quite far, assuming that avoiding hazardous materials, contributes to recyclability and options to use recycled materials. This case showed no direct conflicts for this choice and no major conflicts with lean principles. The eco-design strategy wheel may need some future adjustment with regards to order of assessments. A more detailed evaluation using LCA can then be performed by environmental experts after prototyping, in the production and in the marketing stages. In the prototype stage, technically limitations are considered. In full operations, the economic feasibility will be limited by volumes and material markets. For further research a multiple case study assessment comparing the eco-design strategy wheel with LCA is suggested.

5. Conclusions

The Eco design strategy wheel, based on LCA, was used for continuous improvement of environmental impact in an early stage hot spot analysis. The assessment shows that simple rules to avoid hazardous materials and aims for renewable or recyclable material are important. Since data around materials are difficult to find in early phases the eco-design strategy wheel and green principles can be a help for practitioners to do mostly right. The eco-design strategy wheel may need future adjustment with regards to order of assessment.

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