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DEFINING CO_2 EMISSIONS OF A CONSTRUCTION PROJECT ON THE BASIS OF PROGRAMMATIC INFORMATION

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ABSTRACT

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the delivery process, i.e. defining needs for the product, choice of geometry, and choice of materials (Ashby W.R). Ashby's description is universal, covering all kinds of products. But if we make an interpretation to construction, environmental impact is due to

- programming process (needs for the product),
- massing during preliminary design (choice of geometry), and
- choice of materials during detailed design.

At the moment, CO_2 emissions are mostly defined from the use of materials during detailed design and construction, and from life cycle consumptions based on detailed design. In the detailed design stage, quantities of materials can be measured. And, as the mass of the building, internal conditions (e.g. internal climate) and external conditions (e.g. climate) are known, life cycle emissions can be modeled (or actually, calculated).

The problem is that this kind of approach does not involve a project definition or early massing during preliminary design to challenge designers to consider CO_2 emissions as they steer early design forward.

However, the most important decisions in relation to environmental impact are done during programming and massing in the preliminary design stage. If we set a question whether we need an auditorium or not, the decision made affects vastly more than latter decisions of the materials of the supposed auditorium. The need for an auditorium is not a design problem, rather it is a functional (i.e. programming) problem. And onwards, massing during preliminary design dictates the quantities of the materials measured later (more or less efficient massing, corridors, compact or scattered, more or fewer floors, etc). Longer distances between customer functions affect the quantities of staircases, external wall, air exchange ducts, cabling and site processes during construction in site (Pennanen, Ballard, Haahtela).

The authors argue herein that life cycle analysis (LCA) calculations should be used to help customers set goals, i.e., LCA should be used to steer design. Similarly, LCA should steer contractors and designers in detailed design. If CO_2 emissions are defined only from material quantities of detailed design, analysis is then rather declarative than helping to steer the design, as the calculation happens after the last responsible moment for programming and material selection.

This paper presents a theory and applications to involve the client and early design to proactive steering of CO_2 emissions during programming and early design; allowing all parties

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to collaboratively determine what CO_2 emission goals to set for a project as well as how best to achieve those goals.

KEYWORDS

Lean and green. Product development, value and design management.

INTRODUCTION

The question: "Do we need an auditorium?" cannot be solved by design. Showing a sketch with and without an auditorium does not provide more information to the actual question. Indeed, the answer to the question of whether or not an auditorium is needed is based on a customer's or users' functional needs. By contrast, the decision that a client or users need an auditorium, or they do not, has a large impact on CO_2 emissions during construction and over the auditorium's life cycle. In fact, the decision of WHAT to build is much more significant than a decision of HOW to build it (i.e., what is the frame structure of the auditorium, what kind of finishing, or what kind of air conditioning). Given the impact of the programming decision, i.e., the decision of WHAT to build, it is critical that designers, contractors, and clients understand steering.

And further, massing during preliminary design (i.e. three dimensional geometry defining how functions are located in the building) dictates internal distances, perimeters, projections etc. floor by floor, and thus dictates most of the quantities measured in detailed design (Pennanen, Ballard, Haahtela 2011), (Pennanen 2004).

Understanding this phenomenon, steering in programming and all design phases should be understood.

THEORIES OF STEERING

Theories of steering generally (not only for construction) are introduced under themes of managing complex systems. When construction is considered, complexity arises from different points of views of strategic leaders, operative managers, users, investors, and neighbors among others. And, if we ask for a sketch design from a hundred architects, we will likely get a hundred different solutions.

Theories of managing in conditions of complexity are associated, for instance, with "holism", "feedback", "cybernetics", "cellular automata" and "adaptive systems". Most of the modes of complexity management, especially when social systems are considered, are based on feedback and iteration loops, and assume closed loop production systems. Feedback and iteration loops consists', for example, of owners' wishes, measurement of consequences of said wish (money, time…), withdrawal from original wish, new proposals etc. In contrast to open loop systems, the output produced in closed loop systems is used to adjust or steer the system to its targets. That is done by measuring and comparing actual output to intended. (Simon 1996).

Construction project management requires purpose that are set in the very early phase before design starts. Goals can normally be derived from a customer's strategy. Goals can be addressed to

- functionality
- CO_2,e emissions
- costs
- time
- toxic emissions
- etc.

As the goals are multiple, the models needed to support decision-making should model, rather than one specific item, the entirety of the project itself. For steering, a digital twin of a building that spans over its lifecycle is needed. (Haahtela 1980).

CLOSED LOOP ITERATION

As construction is considered, iteration cannot, of course, be based on constructing buildings, demolishing them, and making better ones.

Steering and closed loop control requires modelling. BIM modelling is not appropriate for modelling customer needs, as those customer needs are its input information.

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the construction process, i.e. defining needs for the product, choice of geometry and choice of materials (Ashby 2013). Calculating costs in both emissions and currency is very similar. You multiply quantities of resources used by the unit cost, in currency or emissions, of using a single resource. Steering projects to goals for reduced carbon and other emissions should and can be added to the scope of project management.

BACKGROUND: STEERING FOR CONSTRUCTION APPLICATIONS

The Underlying theory of steering a construction project (Target Costing of a Construction Project) has been developed in Finland by professor Yrjänä Haahtela in 1980's (Haahtela 1980). Steering is based on a target that is defined before a solution to fulfill the target (in any stage), and then verifying if the solution fulfills the target. If not, a new solution should be created. The target should not be defined by solutions to fulfill the target. E.g. target for proper design (spaces, timetable, building cost, maintenance cost) should not be defined by means of designing, but rather by means of programming.

Steering is possible if for a set of needs (a problem) there are multiple solutions to fulfill the needs. To a simple problem, such as $ax^2 + bx + c = 0$, steering is not needed, as there are two, one or no right answers (among real numbers). You must just learn how to find it. But if you ask a hundred architects for a solution to a single set of customer needs, you will get a hundred different solutions. And that will be repeated with engineers and even with planning the site operations. And before that with programming. The steering concept is aware that there is a big variety in design solutions for a single programming (as well as in programming solutions for a single customer functionality) (Haahtela 1980). It has been studied that there is a weak correlation between costs and architectural soft quality (Niukkanen 1980) among varying possibilities. It means that it is possible to set a steering range of costs of building to be narrower than the range of all possible architectural solutions without losing architectural soft value. And it can be done before design. By means of the concept, design can be steered in targets defined before the design has been started.

The steering concept was set in the early 1980's and has been developed until now. Original application was based on spaces needed in programming (Haahtela 1980), and it was expanded to the actual customer functions in the early 2000's (Pennanen 2004).

Steering a construction project in accordance with complexity management concepts is very simple in concept, though quite difficult in practice.

The steering process is based on:

Defining the goal (functional, financial, CO_2…)

Rapid measurement of the proposed solution to provide the goal

Analyses of whether the proposal meets the goal

Rapid feedback to the actors creating the proposals

- Actions to minimize the difference between the goal and the proposal
- New measurement

Although the steering steps are simple, the steering problem arises from the difficulty to create useful information for management in a complex environment. Suh (2005) defines that a design system has a total amount of information that can be split into two groups, useful and superfluous information. Useful information relates solely to the satisfaction of functional requirement, whereas superfluous information does not affect the relation between the goal and design solution. To succeed, the main focus should be on useful information and superfluous information should be minimized (Suh 2005). If a doctor is asked when programming a hospital, whether he/she requires spatial support for surgery and whether he/she likes brick as a material in external wall, the former information is useful in programming and the latter is superfluous, because only the spatial support impacts the ability of the design to achieve the goal of providing a safe environment for patient care. As the customer and producer change throughout a construction project, so too does the language of usable information (owner or user for project management, owner or user for design, project management to design, project management to contractors, design to contractors). Thus, useful information must be studied through participants and project stages. The goal for the customer likely will not be the number of column footings and attributes of each footing, though these parameters will be useful information for the foundation subcontractor to meet their goal.

In a steering process, proper information is needed quickly and continually to provide management with goals, measurements and rapid feedback. In many cases, modelling is needed to create information (Haahtela 1980), (Pennanen 2004).

INFORMATION USED IN PROGRAMMING FOR STEERING CONSTRUCTION PROJECTS

Ideally, steering in project definition results in the following:

- All customers and stakeholders have expressed their business scope, needs and wishes.
- Business scope has been transferred to language that both the customer and the designer can understand, e.g., activities, spaces, performance.
- Customer knows the costs at completion and is willing and able to pay for the determined benefit and functionality.
- Customer knows the CO_2,e emissions the project will create
- Customer is willing to launch the design process.

INFORMATION USED IN DESIGN

To understand how designing results in cost and CO_2 emissions, it is worthwhile analysing how designs that were initially very complex conceptual designs end in simple detailed manufacturing solutions. Design can be divided into two orthogonal perspectives (Pennanen et al. 2011):

- shape of the building and connections of the functions (concept design)
- building components (detailed design)

The design starts with solving the interdependencies (the connections) between the customer's activities and massing the building in its urban environment. There are numerous possible conceptual solutions for a customer's specification (and for the target cost), and the cost variability is vast. When we deal with concept design, the components, like cooling beams, suspended ceiling or details of external wall are normally not specified. Concept design can be understood as designing for the customer.

When the customer accepts the concept design, designers start to concentrate on determining the building components and materials that can be found in the market and sizing them (detailed design). It lasts until the construction is finished. Detailed design can be understood as designing for production and for the contractors.

Concept design determines the quantities of building components (in a single-floor building there is more roofing than in two-floor building, but fewer stairs). On the other hand, detailed design determines the unit costs of those components. The building cost and CO_2 emissions are a product of these perspectives: quantity times unit cost/CO_2 release.

INFORMATION USED IN LCA CALCULATION

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the delivery process, i.e. defining needs for the product, choice of geometry and choice of materials (Ashby 2013). Thus, Life Cycle Analysis calculation must cover helping the customer to set goals (project definition), steering designers (design) and steering contractors (construction).

If, during project definition, only valuable functions are determined to be built, the size of the building, and also its environmental impact, will be reasonable. Raising the utilization of the spaces by co-using them for many functions leads to smaller total floor area being constructed, which in turn leads to less emissions. Programming might be the most powerful tool to cut CO_2 emissions. In environmental thinking, less really is more.

During design and construction, the CO_2 emissions are due to production of building materials, transportation of the materials and site energy consumption. During the use of the building, emissions are due to energy use during occupation (heating, cooling, air exchange, energy of the user equipment, use of water…), replacing building materials (e.g. replacing heating unit after 15 years) and possible fuels to produce energy for consumption (oil, sun, water, biomaterials). How the building is demolished after use also affects CO_2 emissions. Recycling of the building materials lowers the lifecycle emissions that are caused by producing building materials (Ashby 2013).

LCA calculation requires steering, as target cost and CO_2 emissions values in Target Value Design. The problem is how to define a building level target and component level targets for steering and fast feedback. Otherwise, project teams will calculate what has happened, not what should happen.

In component level simulation the building level targets are assigned to the building components before start of design. Building components can be, for instance, external wall, cooling system, lighting system or nurse call system, material and work. Cost of the building product is easy to find for project management, but how to define the environmental impact of the building materials? There are statistics for most common materials. But more important, an Environmental Product Declaration (EPD) is a standardized way of quantifying the environmental impact of a product (verified in accordance with the ISO 14025). More and more of the producers of building material also inform about e.g. the CO_2 emissions released when producing the product. The project manager gets the cost and CO_2 emissions from the same source.

Innovations and development with modelling systems is needed to enable better steering of sustainability in construction. There already exist models that can support effective space planning and design in relation to business activities.

SIMULATION OF DESIGN AND CONSTRUCTION

Within Haahtela Group in Finland, the problem of various kinds of information concerning just the same building is solved by simulation of programming, design and construction (Haahtela 1980), (Pennanen et. al 2001).

Simulation is based on a fact, that clients, designers and contractor do their decisions in predictive ways, based on function.

The material /equipment use of an operation theatre is big. There is a plant room for circulation fans, ducts and HEPA filters. A 1000 lux lighting and tiling on the walls. Can all these materials and equipment be derived from the requirements of the function: limited particles in air (e.g. ISO5), hygienic surfaces? If so, they can be simulated from the function without designing. If we need a 1000 lux lighting, given assumptions on the lumen values of a luminaire fulfilling the functional requirements, quantities of luminaires can be simulated.

The basis to simulating massing arises from the spaces and function. For example, the need of natural light in rooms, the ability to access certain spaces from street level, and the possibility to locate a function in a basement. The city plan and its external requirements provide the framework for the massing.

The Simulation model uses programmatic information as initial information and results all building elements and components needed for desired functionality. It simulates decision making of real world architects, engineers and contractors. The simulated building can be considered as one possible solution among many others.

RESULTS OF SIMULATION AND COSTS

The literature on cost estimating is in general agreement that the level of accuracy of estimates increases with the specification (and eventually production) of the asset. The earlier the estimate in the life of the project, the lower its accuracy. Consequently, assessments of conceptual estimate accuracy are quite low. An extreme example: "…at this stage [prior to design], almost nothing is likely to be known about the building except its general size, and therefore it is pointless to go into detail about the cost before any designing has been done." (Ferry, et al., 1999). As a result of an incomplete specification of the asset to be constructed, the industry has historically accepted high levels of variance between the estimated and the actual total installed cost. Customarily, during pre-design, the industry has accepted a standard of +/-30 % of variance from estimates, after adjustment for changes in scope.

The previously described wide variance is based on projects that do not have proactive steering process with simulation of project delivery. With projects where proactive simulation has been used during programming and early design, the standard deviation of budgets before the design has been started compared to completed costs is less than 5 %. Thus, it has been shown that the simulation model and steering are powerful tools (Ballard, Pennanen 2013).

POSSIBILITIES TO STEER CO2 EMISSIONS, AS WELL AS COST, BEFORE DETAILED DESIGN

If programming and design simulation can successfully steer the costs of a construction project, it is possible to steer CO_2 emission, too. So that the customers decisions are in the front line, then designers, and finally procurement and construction in site.

In Finland, such simulation is in use, but, at the moment, researchers are lacking results, population of completed construction projects with simulation of CO_2 from early programming and design.

Researchers have made a study, calculating the correlation of costs and CO_2 emissions due to preliminary designs. The project was a day care center in Töölö district, Helsinki. The population was four preliminary design solutions. They were the best architectural solutions resulting from the competition. There were no bad ones, only good ones. One of them was built later.

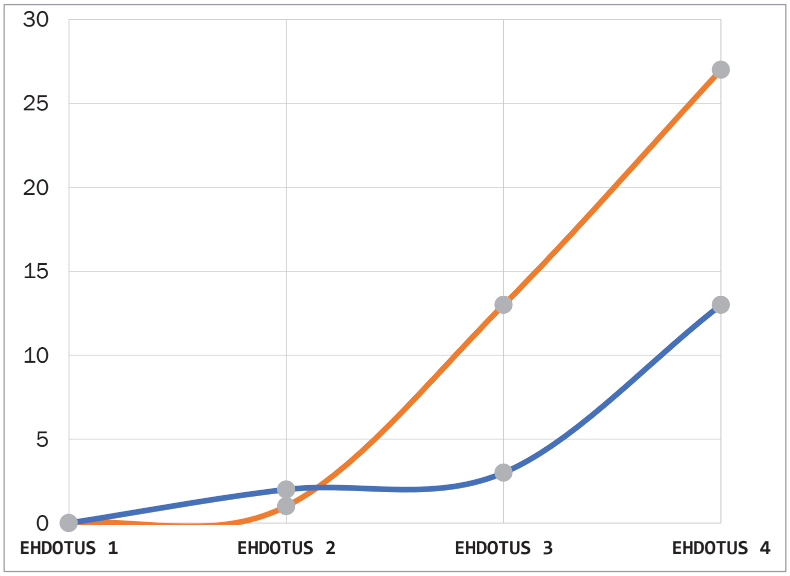

Figure 1: Four Architectural Proposals for a Single Programming of a Day Care Center. Blue curve: Cost variance of the proposals (%). Red curve: Variance of CO_2 emissions of construction (%) (Harvala A. 2022).

Ehdotus (Proposal) 1…4 are alternative design proposals for the same programming. Lower curve describes construction costs (0…13 %) and upper the CO_2 emissions of construction (0…27 %) (Harvala A. 2022).

The first conclusion (based on very low population) is that variety among proposals is high in relation to costs and CO_2 emissions (that was supposed basing previous research). Variety of soft architectural quality in this population is low, as the best four proposals are considered. The phenomenon is a subject of steering, from programming to the use of the building! As the correlation between costs and CO_2 emissions is strong, the researchers suppose that the proven methods to steer costs can be applied to CO_2 emissions.

In conclusion, simulating and steering projects from their earliest stages allows stakeholders to consider and actually change the environmental impact of the construction before the realization of the emissions. While costs in building projects have been considered this way for longer, they mainly impact only the stakeholders themselves. The emissions, however, impact the entire planet. It would thus seem prudent to utilize simulation and steering in project management, for both costs and especially CO_2 emissions.

FUTURE RESEARCH

Simulating CO_2 emissions from programmatic data has just begun. The investors get information of CO_2 emissions before design, based on their decisions. And later based on the designs as well.

Researchers need more evidence from on-going projects. It seems that it can be provided.

On the other hand, life cycle emissions are not included in this research. The simulation model, as used for predicting function and massing, is also capable to steer life cycle emissions. That is the issue of another paper.

REFERENCES

Ashby, W.R. (2013). Materials and the Environment. *Elsevier Inc.*

Ballard. G, Pennanen A. (2013). Conceptual Estimating and Target Costing. *21th Annual Conference of the International Group for Lean Construction. Fortaleza, Brazil.*

Ferry, D.J., Brandon, P.S., & Ferry, J.D. (2002). Cost Planning of Buildings, *7th ed. Blackwell Science, Oxford, 376 p.*

Haahtela, Y. (1980). Talonrakennuksen normaalihintamenettely (Target costing methodology in construction), *Helsinki University of Technology (in Finnish only)*

Harvala. A., Rakennushankkeen hiilijalanjäljen ohjaaminen hanke- ja ehdotussuunnitteluvaiheessa (Steering CO_2 emissions during programming and early design). *Tampere University of Technology*

Niukkanen, I. (1980). Quality and Cost Factors in Architectural Design (Rakennussuunnittelun sisällön ohjaustekijät). *Helsinki University of Technology, Department of Architecture (in Finnish only).*

Pennanen, A., 2004. User activity-based workspace definition as an instrument for workplace management in multi-user organizations. PhD Dissertation, *Technical University of Tampere and Haahtela-kehitys.*

Pennanen A. & Ballard G. (2008). Determining expected cost in the target costing process, *Proceedings of the 16th annual conference of the International Group of Lean Construction. Manchester, U.K*

Pennanen, A., Ballard, G., Haahtela. Y. (2011). Target costing and designing to targets in construction. *Financial Management of Property and Construction.*

Simon, H.A. (1996). The sciences of the artificial. *The MIT Press, London*

Suh N.P. (2005). Complexity, Theory and Applications. *Oxford University Press*.