DESIGNING THE TRANSPORT ORGANIZATION OF A SMART FACTORY FOR THE MASS RETROFIT OF HOUSES IN SWEDEN

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ABSTRACT

Purpose

Growth in population and urbanization led to the infrastructure project "Swedish Million Programme". One million dwellings were built in the 1960s. Today, most of these buildings generate excessive CO_2 emissions due to their architectural standard. This enormous number of dwellings to be renovated marks a challenge for production and logistical processes. To tackle the need for rapid renovations, the project INDU-ZERO was initiated. A smart factory is designed to speed up the renovation pace to 15,000 dwellings per year. This paper aims to find out which transport modes are best suited for these renovations.

Methodology/approach

The study follows the design-science research process. The research gap was identified based on a literature review. Understandings gained in this process were further compared within the INDU-ZERO case study.

Findings

In order to renovate the large number of buildings and organize their transportation planning, a transport calculation tool was designed, which determines the most efficient mode of transport after entering the parameters destination and number of apartments.

Research limitations/implications

Since not all houses can be considered individually, a clustering into cities and regions is carried out.

Practical implications

The paper presents a calculation tool for the specified use case that combines economic and sustainable aspects and carries out a choice of transport mode, a cost consideration as well as a CO_2 balance.

Original/value

For the first time, the logistical supply of construction sites for industrialized renovation of specific buildings in Sweden is studied.

Keywords: Swedish Million Programme, building industry, smart factory, route-planning, transport network

1 INTRODUCTION

The European building stock is in high need of refurbishment due to its contribution to excessive global energy consumption. In the North Sea Region (NSR) alone there are 22 million houses built between 1950 and 1985 with annual CO_2 emissions of 79 Mton. Current deep retrofits are carried out on a limited-scale production, which may result in climate targets not being met in time. In the near future, a major restructuring has to take place to tackle the high need for renovation of the building stock as here caused CO_2 emissions contribute to around 36 % of the European CO_2 emissions (European Commission, 2019) (European Environment Agency, 2015).

This paper focuses on the sustainable renovation of real estate in Sweden. Due to growth of the Swedish population in the 1960s and 1970s and increasing urbanization in metropolitan areas such as Stockholm, Gothenburg and Malmö, the government came under strong pressure. As a result, the large-scale infrastructure program "Swedish Million Programme" was initiated. The construction of a total of one million new rental apartments in accordance with the energy standards of the time remarkably eased the situation. However, this resulted in a noticeable decline in the number of new buildings in the following decades since the demand for housing had been met. A large proportion of the today 50 to 60 years old buildings are now again coming into focus due to a lack of maintenance and outdated technology, particularly with regard to energy efficiency.

To tackle the urgent need for rapid renovations in the NSR, six countries (the Netherlands, Belgium, Germany, United Kingdom, Norway and Sweden) collaborate to upscale the current renovation process in the Interreg project INDU-ZERO “Industrialization of house renovations toward energy-neutral”. The project focuses on modular prefabricated renovation packages to arrive at energy-neutral dwellings. The project researches the possibilities of far-reaching automated and industrialized production processes. A smart factory blueprint will be designed to speed up the renovation pace to a target of 15,000 renovation packages per year per factory suitable for all NSR countries while cutting the current price with 50 %. These packages consist of facade and roof panels, which are complemented by photovoltaic systems as well as heat pumps and ventilation systems.

The large number of apartments to be refurbished additionally presents a logistical challenge in which ecological and economic aspects must be combined. Thus, the aim of this paper is to provide a planning approach for a logistics network in Sweden that makes energy retrofits feasible to sustainably reduce CO_2 emissions from the two main sectors of building and transport. The research question of this study can be summarized as follows: Based on the findings from a literature review dealing with transport mode choice and network development applied to a case study, how can thousands of buildings in Sweden be renovated each year, and which modes of transport are most suitable, taking sustainability aspects into account?

The outline is as follows. The INDU-ZERO approach is explained in section 2. The applied methodology is introduced in section 3. In section 4, the theoretical background is explained. Here, a comparison of the different transport modes in Sweden is made. In section 5, an overview is provided of which transport modes are most suitable for which Swedish regions. Furthermore, the transport calculation for the distribution of construction elements for the renovation of buildings in Sweden under ecological and economical aspects is shown. Lastly, section 6 discusses the results, summarizes the recommendations for future research and concludes the paper.

2 THE INDU-ZERO APPROACH

To achieve the EU's climate targets, about 150,000 buildings per year should be renovated in Sweden in the period 2022-2030. However, the renovation speed is too low to deal with these numbers. Today, there are only a few production facilities that can offer renovation solutions for a maximum of 500 dwellings per year. In this case, each dwelling is still supplied with specially tailored proposals and the work is mostly done on-site. As a result, the costs of renovations to energy-neutral homes, which often exceed €110.000 per unit, is too high to convince homeowners of an energetic renovation (Lange and Krämer, 2019).

In the future, as a result of Industry 4.0 and digital transformation, it will be possible to produce entire house units in a decentralized manner in smart construction factories that aim for a standardized, cost-effective and faster production of residential properties compared to conventional construction on-site processes (Vestin *et al.*, 2018) (Tetik *et al.*, 2019). Standardization is highly developed to have a more cost-effective and faster production due to a configure-to-order approach. By manufacturing according to an industrial scale, housing shortage can be counteracted. Furthermore, these factories can target the market for old buildings and renovation projects as the production of customized renovation packages is also possible (Zander *et al.*, 2020).

The project INDU-ZERO aims to develop a blueprint for a production facility, based on smart industry and circular economy, that can produce wide suitable renovation packages at a high volume (15.000 units/year) at low cost (50 % of current price) per factory. The intention of the design of the renovation packages is to achieve energy-neutral dwellings in one-step. The facade and roof panels are developed considering several design boundaries such as production speed, environmental impact on CO_2 reduction and total cost of ownership. They are designed for semi-detached houses, terraced houses and apartment buildings. The structure of the developed renovation packages is independent of a specific project or building. The aim of this mass-customized approach is to eliminate construction as well as on-site complexities and constructability issues, as the panels always follow the same production and mounting processes. Moreover, the packages have to be pre-assembled as much as possible before being transported to the construction site, to cut down labour time, total costs and nuisance on-site (Decorte *et al.*, 2020).

Based on the standardization, it is possible to develop suitable renovation packages for each type of house and copy the factory floor plans. Consequently, a factory is to be built in each of the project's six partner countries to meet local needs and prevent long transport distances. In regard to Sweden, the construction of such a smart factory could be planned in Kristinehamn focusing on the renovation of the buildings built during the Million Programme period. This is due to the fact that Kristinehamn is centrally located and has good infrastructure connections. In addition, the country's largest expended polystyrene manufacturer has its production facility here, which means that the smart factory can be perfectly supplied with insulation material.

3 RESEARCH METHODOLOGY

The subject of the work is the development of a transport network for a smart factory in the construction industry in Sweden. As the objective is to design, use and manage a transport system more efficiently, the development can be carried out according to the design science (DS) research method according to Hevner *et al.*, 2004. It is a problem-solving-oriented approach, in which design artefacts are created and evaluated on the basis of scientific and practical criteria in order to solve organizational problems. The focus of DS research is the understanding of different, existing phenomena (research) as well as the creation and development of something new (design). The selection of DS research is imbedded in the discussion of rigor and relevance of scientific knowledge, i.e., the problem of scientific foundation while considering practical relevance (Gregor and Hevner, 2013).

One possible framework is the DS process developed by Pfeffers *et al.*, 2007, which also serves as a process model for this paper. It describes a structured method for the development of artefacts according to the DS approach with the aim of providing a mental model for the characteristics of the research results (see Figure 1).

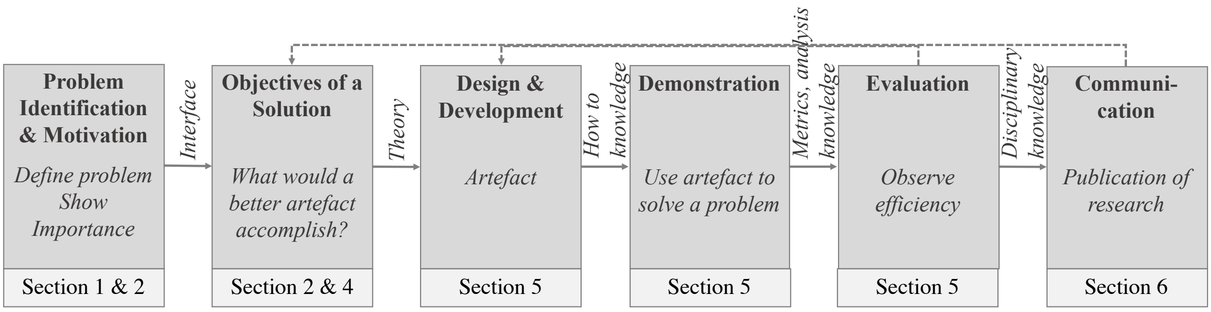

Figure 1: Design Science Research process

The DS process is divided into six phases:

1. Identification of the research problem, presentation of the motivation to find a solution, and demonstration of the relevance of the added value to be researched.
2. Definition of qualitative and/or quantitative goals of the artefact derived from the research problem
3. Development and design of the artefact and its architecture
4. Demonstration of suitability for problem solving through case studies, simulations, experiments, or surveys
5. Evaluation of the problem solution quality as well as comparison with equivalent solution approaches
6. Communication of the solution to the research problem.

If the output of the evaluation or communication phase does not meet the specified standards, which could further lead to an unacceptable result, it is necessary to go back to a previous phase in order to improve the solution approach at an early stage (Pfeffers *et al.*, 2007).

To capture the state-of-the-research and theoretical background comprehensibly, the research gap was identified based on a literature review according to Baker, 2000. One qualitative-explorative research goal was pursued: the analysis of the infrastructural preconditions for the transport modes in Sweden. Based on the literature review, the findings were evaluated with insights gained from the INDU-ZERO project to create a specific artefactual solution, which represents a procedural model for the implementation of smart factories in the NSR, independent of the country.

4 THEORETICAL BACKGROUND

In the following sections the theoretical background necessary for this paper is discussed. A comprehensive literature analysis according to Baker, 2000, was initially performed to identify possible transport modes and routes in Sweden for the distribution of building elements as well as key aspects of logistics network planning. The literature review was conducted using Scopus, Elsevier and EBSCO-host in February and March 2022 focusing on peer-reviewed literature. The found papers and its journals were selected with regard to the VHB-JOURQUAL 3 ranking. Nevertheless, this was just for a ranked selection of the articles listed with a JQ3-rating A-B. Papers from journals that are not mentioned in one of the ratings were not rejected in principle. The following variety of keywords was used:

- (<route plan*> OR <transport* plan*> OR <logistics network development>) AND
- (<mode of transport*> OR <road transport*> OR <railway transport*> OR <waterway transport*> OR <combined transport*>) AND
- (<Sweden> OR <Million Programme>) AND
- (<building industry> OR <construction industry>)

Keyword category one focuses on the development of organized route planning and logistics networks, category two on different modes of transport and the third is about Sweden and its Million Programme and the fourth deals with the building industry. In course of a separate consideration of the individual categories, the necessary background knowledge about the structure of a logistics network, the different modes of transport and their advantages and disadvantages as well as about the Million Programme and building industry can be obtained, which is needed in the later result development. The common consideration of all categories further leads to the identification of reference objects, which also aim at the transport planning in Sweden and can thus be used in the solution development.

The literature review resulted in 370 papers, which support the scientific knowledge progress and represent the final relevant database for the analysis and concept development. The steady increase shows that the examined topic seems to gain popularity and is surveyed more deeply, as sustainability aspects gain importance in the building and logistics sector (see figure 2).

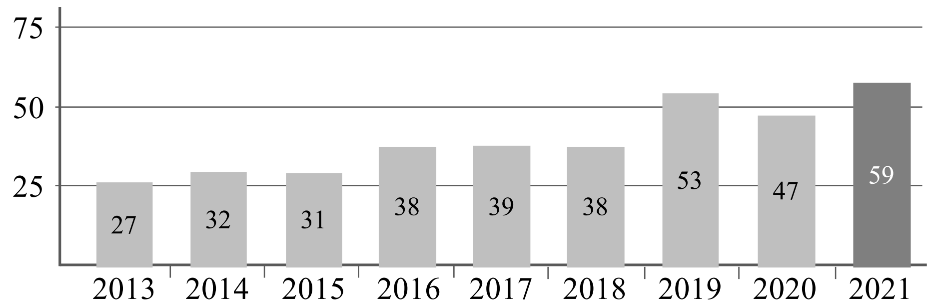

Figure 2: Number of publications since 2013

The final 370 identified publications were then evaluated by using a qualitative data analysis according to Flick (2014) to perform text mining and a content analysis. The analysis used the following two fields in particular:

- Field 1: (<panels> OR <facade> OR <roof> OR <refurbishment> OR <renovation>)
- Field 2: (<cargo transport> OR <freight transport> OR <goods transport>)

Both categories refer to the transport of cargo, since a differentiation must be made between goods and passengers. Field 1 was used to examine the transport of building materials for energy-efficient refurbishment. Since this resulted in only a few results, freight transports of other materials were also examined on the basis of field 2. In the final full reading stage, 83 papers were classified.

4.1 Comparison of transport modes and routes in Sweden

There are different published strategies for supplying building sites in the NSR, especially in Sweden (Pettersson, 2013) (Hammes, 2021) (Flodén, 2007). In context of this paper, direct delivery (road transport) and multimodal/combined transport (CT) (road and rail freight transport) are considered. The process of direct delivery involves the collection of goods from the production site, which is followed by long-distance transport to the destination area in the main run. There is no transshipment during the entire transport and no change of transport mode, which reduces the transport time and risks of damage. Transport volumes are decisive for the cost-effectiveness of direct delivery. Only with a high utilization transport costs per unit can be kept comparatively low through consolidation effects. In case of time-critical shipments, direct delivery is usually preferred (Clausen and Geiger, 2013).

In CT, goods are also picked up from the production site but are then transported to a transshipment point. Goods are transshipped, sorted and consolidated depending on the respective destination. In the main leg, consolidated goods are transported to the destination area before being transshipped again for the onward leg to the destination. Depending on the location of the transshipment point, the transshipment may also involve a change of transport mode (Clausen and Geiger, 2013).

The choice of transport mode is of strategic importance for the provision of the transport service. In general, all transport modes fulfill the requirements for transport of building panels for retrofit of houses in different ways. For the analysis of the infrastructure conditions in the NSR, values of the Netherlands and Germany are also included (see Table 1).

Table 1: Transport infrastructure in the NSR (in km)

Mode of transport / country	Sweden	Norway	Netherlands	Germany
Road	215,690	95,494	139,690	229,826
Inland waterways	0	0	6,297	7,675
Rail	10,906	4,134	3,220	39,299
electrified (%)	75,3 %	59,5 %	70,7 %	52,9 %

The table shows the infrastructural conditions for both road, inland waterways and rail freight transport, with a comparatively extensive road network and a good electrification rate of the railroads of 75 % in Sweden (European Commission, 2020). Since the inland waterways are not used commercially, they are not considered in the following and are only listed for comparison purposes. In the following, the modal conditions for road and rail in the country under consideration are evaluated and their KPIs are shown, as these play the decisive role in the subsequent transport calculation.

4.1.1 Road transport

The advantage of the truck is the high flexibility due to a direct connection for almost all routes. This results in a cost advantage due to the elimination of a pre-carriage and on-carriage as well as the associated cargo handling and safety risks. The flexibility also favors the use of road freight transport in pre- and onward legs of a multimodal transport chain. With a maximum range of 800 kilometers per day, trucks are the most powerful mode of transport together with freight trains. The range is primarily limited by speed limits on roads and regulations on breaks for drivers (Gudehus, 2012). Sometimes flexibility is also limited by driving bans on Sundays and public holidays. However, these do not apply in Sweden (BMDV, 2020).

To measure the criterion of safety, accident figures involving goods road transport vehicles are considered. These have been on the decline since 2017. In 2019 a total of 36,939 accidents involving goods road transport vehicles were recorded in Europe by the Federal Statistical Office. Compared to the previous year, the number of accidents involving serious damage to property decreased by 7 %. Sweden does even better in the aspect of road safety. With only 22 traffic fatalities per 1,000,000 inhabitants in 2019, Sweden occupies the top spot in Europe (European Commission, 2020).

A quantitative assessment of network capability is often a challenge, as there is no comparable indicator for the mode of transport. Therefore, only the extent of the transport network and the possibility of CT are covered by the criterion of network capability. In particular, the transport route network of the truck can be rated as very good with the connection of every location to the railways network. For optimal use of CT, a total of ten inland cargo rail terminals are available in Sweden along the core network corridor (BMDV, 2021).

Since the use case of this paper involves long transport distances of building elements, the measurement parameter for the transport costs is €/km and €/wagon/km. This ratio has the advantage that it considers economies of scale, which can be identified by a degressive development of transport costs per unit with an increased transport capacity. Since transport costs depend to a considerable extent on the respective transport service provider and thus on external circumstances, average values are used in the further course of the calculation. As already mentioned, the transport capacity plays an overriding role for the calculation tool. A truck can transport six renovation panels. Using an articulated train consisting of a truck and a trailer results in a total transport capacity of twelve panels.

In terms of delivery time, the truck, with an effective speed of around 60 km/h, occupies a top position. Disadvantages of trucks are high fuel consumption and associated emissions. On average, a semi-trailer truck consumes between 35 and 40 liters of diesel per 100 km (Gudehus, 2012). Particularly in the case of transports over long distances in Sweden, rail transport is primarily used as a functional alternative when a decision is made on basis of sustainability aspects. In addition to emissions, another disadvantage of truck transport is its susceptibility to weather conditions and traffic disruptions.

The aspect of susceptibility to traffic-related disruptions during transport by truck can prove problematic in that a planned Just-In-Time (JIT) delivery would delay all downstream processes, e.g. on-site mounting of the building panels. Applying the key performance indicator system results in the following performance profile for road freight transport (see figure 3).

Figure 3: Performance profile for the truck

Overall, the truck is suitable as a means of transport for the transport of building panels in Sweden, due to its flexible use and high speed, especially for pre- and on-carriage in CT, combined with the good infrastructural conditions. Its long-range also favors its use for time-critical transports that have to be carried out within one day. In order to make the most of the truck's strengths, these results are integrated into the transport calculation. This classification is made in section 4 in connection with the definition of the model for transport costing.

4.1.2 Rail transport

Rail freight transport refers to transport by means of a traction unit and freight wagons. Due to the characteristics of rail freight transport, long land-based transports are mostly carried out by rail. This mode of transport is often used for the main leg of CT.

Energy efficiency in the main leg, which is possible due to low rolling resistance between wheel and rail, especially with high payloads, is a positive feature. The spatial and temporal flexibility of rail freight transport is limited by the track connection, which means that this mode of transport has a considerably weaker network-building capability compared to truck transport (de Miranda Pinto *et al.*, 2018).

The network capability of rail is limited by the restricted development of the rail network in relation to roads. This factor varies depending on the expansion of the infrastructure. The Swedish rail network with ten existing cargo rail terminals has a good network capability due to the advanced expansion, however, the network capability of rail still lags significantly behind, especially compared to road, as long on-carriage times can be required (BMDV, 2021).

Safety is generally considered to be relatively noticeable due to the lane guidance as well as generous safety distances (European Commission, 2020). Nevertheless, risks of damage must be considered in transshipment operations. The share of damaged goods is estimated at approx. 3 % (Gudehus, 2012). In addition, long transshipment operations can negate previously gained cost and time advantages.

Railways show a positive performance for the criterion of transport capacity. A block train with 25 standard wagons can transport about 300 building panels with optimum loading. This corresponds to the capacity of 25 articulated trucks. Due to its high mass transport capacity, rail is therefore a suitable mode of transport for covering long distances with high transport volumes. With an effective speed of between 30 and 60 km/h, the train is as fast as a truck. Thus, railways are suitable for a main run and long-distance transports not only because of their energy efficiency, but also because of their range of about 800 km per day (Gudehus, 2012).

In terms of sustainability, the train also represents a positive alternative. In particular, the ongoing electrification of rail, in which Sweden is playing a pioneering role in Europe, can sustainably reduce the train's CO_2-eq emissions (European Commission, 2020).

The vulnerability of rail to external influences is considerably lower than that of trucks. On the one hand, the traffic volume of rail is significantly lower than that of road, and on the other hand, rail freight transport is subject to fewer restrictions than road freight transport. Legal bans on truck driving on Sundays and public holidays can be cited as an example of this. Only weather-related influences, such as falling trees and resulting blockages of the tracks or an interruption in the power supply, can have a negative impact on the reliability.

Lastly, freight transport by rail has so far been cheaper than transport by truck in most cases, but rising costs threaten to wipe out this advantage. This is according to a study by rail freight corridor ScanMed RFC (Scandinavian Mediterranean Rail Freight Corridor). According to the research, the cost increase for road transport in the coming years is lower than the other modes. The market position of rail freight transport could suffer if no appropriate measures are taken (ScanMed RFC, 2020). A representation of the performance of the rail is visualized in figure 4.

Figure 4: Performance profile for the train

In summary, rail transport is suitable for a main run over long distances with high transport volumes, especially in Sweden. Likewise, this mode of transport should be regarded as resource-saving due to its sustainable mode of transport. This interpretation is confirmed by the performance profile system (Sivilevičius and Maskeliūnaitė, 2018). The described characteristics of the rail mode of transport will be applied in the transport calculation, especially if a transport service is provided in CT.

4.2 Logistics network planning

Contemporary logistics systems are based on the concept of flows in a network, in which goods, finances and information flows from sources via intermediate nodes to sinks, overcoming spatial and temporal differences as well as company boundaries. The spatial/temporal change of goods is often accompanied by a transformation in terms of quantities, varieties, handling characteristics and information (Mattfeld and Vahrenkamp, 2014).

As a second aspect of the literature research in this paper, methods for logistic network planning were investigated. The objective of this section is to identify and analyse the main methods, tools, their scopes, and integration approaches, to apply one of them in the later use case.

Logistics network planning contains making decisions about the quantity, location, and capacity of logistics facilities along the supply chain, as well as choosing suppliers, allocating products to factories, choosing distribution channels, and transportation modes as well as determining material flows through the network. The purpose is to meet customer demands in time and reduce fixed and variable costs of procurement, production, storage, and transportation (Cordeau *et al.*, 2006).

There are two basic types of transportation networks: land-based transportation networks (road and rail networks) and networks of airlines or ocean-going vessels. Land-based transport networks are characterized by the fact that there are only direct links to geographically neighboring nodes. Each node has an edge to a node that approximates the smallest linear distance to nearest nodes. Paths to more distant nodes cannot be realized via direct links, but only via intermediate nodes. In a procurement and supply network nodes represent the involved partners. Since the network consists of different partners, the nodes are identified by attributes. In addition, arrows can indicate supply relationships between the parties .

Researchers and practitioners often separate logistics network planning into strategic, tactical, and operational decisions. Due to the interdependence among these levels of decisions, their integration can bring important cost reductions and better network responsiveness in scenarios where there is business change (Jalal *et al.*, 2021). The strategic level contains long-term planning that affects the organization and capacity of the network. The tactical level refers to medium-term decisions related to the allocation and distribution of materials and products among the facilities. The operational level includes decisions related to production, warehousing, transportation, and realizing demand operations (Gebennini *et al.*, 2009). The effect of strategic level decisions lasts over a larger period (several years) than tactical decisions, as they deal with decisions that cannot change easily. Tactical decisions have time horizons of months and operational decisions are usually made on a daily basis (Jalal *et al.*, 2021) (Hiassat *et al.*, 2017).

The timing between these decisions should be considered in logistics network planning, as they determine the planning horizon. At the operational level, managers make daily or weekly decisions. Here, information such as demand, lead times, prices, capacity, costs, and procurement availability are less uncertain. Short-term operational decisions can be revised each work period. The tactical level corresponds to the multi-period horizon. The detailed nature of the planning periods requires the aggregation of the work periods and operational decisions. These medium-term decisions are handled from monthly to annual periods. In particular, it is necessary to decide which external/internal modes will be used. At the strategic level, long-term decisions are made, which are generally decisions related to network design for annual to multi-year periods, such as collaborations, the construction of real estate, or purchase of vehicles. The elapsed time between network design and the period of use implies that these decisions are made with partial information (Jalal *et al.*, 2021) (Amiri-Aref *et al.*, 2018). Common to the above systems is their representation with graph-theoretic tools: nodes, edges, and optionally weights attached to the edges.

5 USE CASE: DISTRIBUTION OF CONSTRUCTION ELEMENTS IN SWEDEN

The use case to be examined includes the renovation of houses and apartments as part of the Swedish Million Programme. To end the housing shortage once and for all, the Swedish parliament decided that a million new dwellings should be built in the period 1965 to 1974. The quantitative framework for the renovation needs of this research framework must be elaborated first. This includes the number and relative proportions of rental housing units to be renovated for all cities considered in Sweden. The percentage has then been applied to the production capacity of the Smart Factory in Kristinehamn of 15,000 dwellings per year.

Table 2: Demand for energy refurbishment of Million Programme buildings in Sweden

Country	Region	City/Cities	Rental apartments	share (%)	Panels delivered p.a.
Sweden	Stockholm	Stockholm	43,600	25.25 %	3,787
Sweden	Västra Götaland	Gothenborg	36,300	21.02 %	3,153
Sweden	Skåne	Malmö & Helsingborg	21,800	12.62 %	1,893
Sweden	Östergötland	Norköping	12,600	7.3 %	1,094
Sweden	Gävleborg	Gävle	8,700	5.04 %	755
Sweden	Örebrö	Örebrö	8,700	5.04 %	756
Sweden	Södermanland	Södertälje	7,300	4.23 %	634
Sweden	Jönköping	Jönköping	6,800	3.94 %	591
Sweden	Uppsala	Uppsala	5,800	3.36 %	504
Sweden	Värmland	Karlstad	4,800	2.78 %	417

The figure shows that logistics network planning must be carried out in particular for the cities of Stockholm, Gothenburg, Malmö and Helsingborg. These regions had a strong focus due to the program's construction activity and are therefore of great ecological importance for renovation activities.

Since an average of three days is planned for the renovation of a residential unit, the form of delivery and the mode of transport must ensure JIT delivery. It is therefore crucial to avoid delays and damaged components. In the end, the strengths of all modes of transport have to be combined and are to be integrated into the transport calculation in such a way that the recommended course of action for the form of delivery ensures the fastest, most cost-effective and sustainable possible transport.

5.1 DEVELOPMENT OF A TRANSPORT NETWORK

To design a geographical logistics network for land-based transportation, the network modelling method is applied according to Mattfeld and Vahrenkamp, 2014, and projected onto the use case. This method is suitable for representing cross-company material and goods flows in a logistics network. The selected model is a static model without time structures (single period). The approaches are based on the well-known static models of localization theory, but extend them by the multiple hub concept and by connections between hubs, which are characterized by economies of scale. The model is able to allow logical intermediate stops on the way to the destination. In analogy to the classical location theory, the model asks the question how many hubs are necessary to establish a minimum cost transportation network with hubs. This is especially important with respect to the Million Programme, since not every building can be supplied individually in point-to-point transit.

First, the respective transport parameters have to be defined and visualized with graph-theoretical tools, i.e. nodes, edges and weights attached to the edges. The edges, here the cities of the Million Programme in Sweden, were mentioned in the previous chapter. The nodes, here the transportation network, are oriented to the Swedish road and rail network, transshipment terminals as well as their distances between them. The weights describe the number of rental apartments (see figure 4).

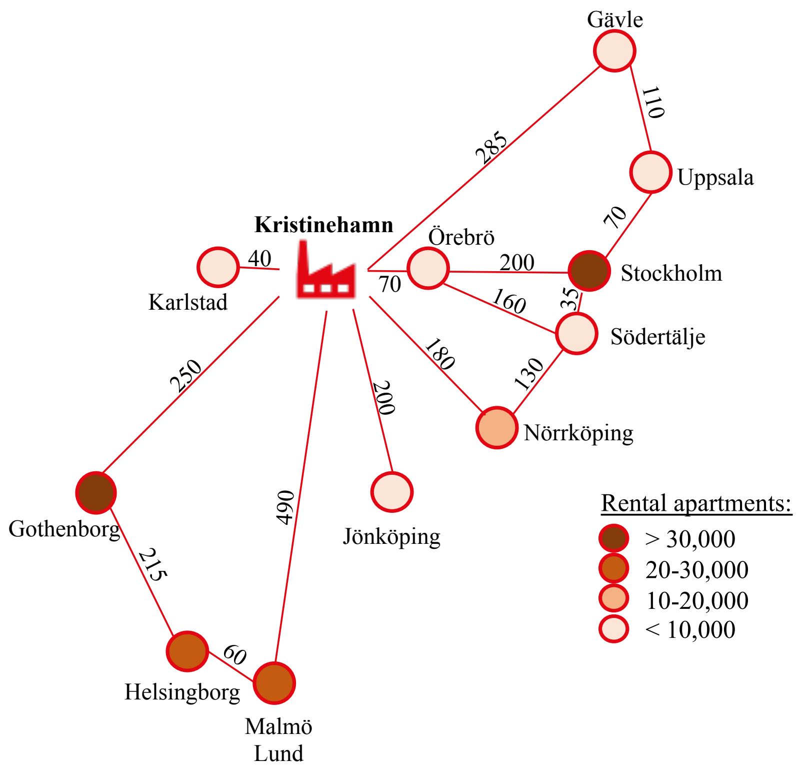

Figure 4: Network modelling based on the example case

Such a model reduces reality to a few features essential for transportation. With a few exceptions, such as Jönköping, this network is an undirected network, since routes can be driven in different directions. Consequently, other characteristics determine the best possible route. At this point, the previously determined KPIs, e.g. speed, CO2 emissions or transport capacity, of the road and rail modes of transport are relevant.

The calculation is based on the Dijkstra's Algorithm, which finds the shortest path between the source node and all other nodes in a graph. This algorithm uses the weights of the edges to find the path that minimizes the total distance (weight) between the source node and all other nodes (Festa, 2007). The structure of the calculation can be followed with the help of Figure 5. First, the general inputs, such as the departure point (Kristinehamn) and the selected destinations, are presented. For these inputs, the two possible transport methods are compared. After displaying the facts about the transport (distance, transport time and earliest arrival date), the most relevant KPIs are displayed in the two right columns: transport costs and CO_2 emissions. The calculations are based on default values for costs and emissions.

For truck transport, the algorithm considers the transport distance from a previously created distance matrix. For CT, the transport distance is further divided into separate "stages", first from the production site to the nearest transshipment point, then the main transport to the nearest transshipment point at the destination, and finally the onward leg to the final delivery point. The shortest path algorithm, implemented by a formula, guarantees the shortest connection for each destination in terms of transportation distance. From the distances and the weight of the facade and roof panels, the ton kilometers can be calculated, which serve as the basis for the emission calculations and capacity requirements.

Based on the algorithm, it is clear that the "break-even" in terms of emissions is between 200 and 300 km transport distance. Below 200 km, the truck is always the more efficient mode of transport; for distances of more than 300 km between the production site and the destination, CT definitely shows the strengths of economies of scale and ecological advantages. When considering transport costs, CT is almost constantly more expensive, as there are two reloads and transport by rail is more expensive than transport by truck.

Another feature of the calculation is the best possible utilization of transport capacity by combining the renovation needs of several cities or construction sites that are located close to each other or are in the same cardinal direction. With this method, the truck can make a round trip directly or in the wake of a hub, for example, transporting panels to Stockholm and using the remaining capacity for construction in Uppsala in the same transport operation. Combining the needs of several cities by forming a cluster for each cardinal direction can contribute significantly to the effective use of resources.

5.2 TRANSPORT CALCULATION AND RESULTS

Now that the transport network has been presented as the artefact of this paper, it is necessary to demonstrate its usefulness in practice with the help of a simulation in accordance with the DS process. For this purpose, a planning tool was designed for the specific use case and the algorithm was integrated. Simulations are often used when planning the implementation of new process structures. The performance of the logistics system is analyzed and described so that the implementation can run without errors. The calculation model is also analyzed using a simulation of the use case. In this way, deliveries can be planned effectively by means of demand-oriented prioritization, which is a decisive basis for the logistical supply of the construction sites. In the following, the transport calculation is checked by entering destinations to see to what extent the output results plausibly fit the use case. The simulation considers one destination each with a small, medium and large distance to the production plant. At the same time, the selected relations should show relevance for the renovation project by the percentage of the total demand. The performance and scope of the transport calculation validated by the simulation. In addition, a comparison is made between the recommendation of the calculation tool and the planning of a truck transport without supporting calculations as the evaluation step of the DS process.

The following cities were selected for simulation:

- Stockholm (direct distance to factory: 270 km)
- Södertälje (direct distance to factory: 230 km)
- Örebrö (direct distance to factory: 70 km)

First, the example of delivery to Stockholm is examined for this purpose. Stockholm is to be supplied with 500 renovation panels in this simulation, and the proposed cities Södertälje and Örebro with 300 and 350 panels, respectively. The time is randomly selected. Entering these data provides the following result (see figure 5):

Departure	Destination
Kristinehamn	Stockholm
Transport prioritization	1
Örebrö Södertälje Stockholm	

Örebrö

Transport method	Requested Panels	Transport distance Departure to Destination (km)	total transport time (days)	earliest arrival time	latest arrival time	total transport costs (€)	total CO2e Emissions (t)
direct transport	500	71	0,22	29.07.2021	29.07.2021	5.039,58	3,44
combined transport	500	241	1,52	30.07.2021	30.07.2021	26.217,51	8,17

Södertälje

Transport type	Requested Panels	Transport distance Departure to Destination (km)	total transport time (days)	earliest arrival time	latest arrival time	total transport costs (€)	total CO2e Emissions (t)
direct transport	300	231	5,43	29.07.2021	03.08.2021	9.759,75	6,68
combined transport	300	344	3,14	30.07.2021	02.08.2021	24.982,50	4,07

Stockholm

Transport type	Requested Panels	Transport distance Departure to Destination (km)	total transport time (days)	earliest arrival time	latest arrival time	total transport costs (€)	total CO2e Emissions (t)
direct transport	350	271	5,93	04.08.2021	09.08.2021	13.739,70	3,76
combined transport	350	331	4,76	04.08.2021	07.08.2021	25.996,50	2,29

Figure 5: Simulation result for the supply of East Sweden

For Örebrö, the result shows trucking in direct transport as the most efficient form of delivery due to the short transport distance. The three results for speed, transport costs and emissions show further advantages over CT. For deliveries to Södertälje and Stockholm, CT can be considered sustainable, especially in view of the low transport emissions. Due to long transshipment times, CT delivery usually takes longer than direct delivery by truck. However, the simulation shows that the effect of the extended transport time due to transshipment operations is relativized depending on the transport distance to be covered. In this example, CT is predominantly recommended with regard to the results of the main efficiency parameters and the CO_2-eq emissions caused. By increasing the transport volumes over long distances, the scale effect is additionally evident in the cost consideration. In addition, the transport costs of CT depend on the connection to the logistics network corridor.

For high transport volumes and long transport distances, the efficiency of CT is demonstrated by the economies of scale that occur. Here, besides the selected cities, Malmö and Lund are characterized by a good connection to the core network corridor, which enables a short pre- and onward carriage, which means that CO_2-eq emissions can be almost halved compared to direct truck transport. Despite the higher emissions due to a long on-carriage, this form of delivery is to be preferred against the background of the parameters for measuring efficiency.

Logistics costs for this massive infrastructural program are around € 12.000.000. By choosing the most efficient transport method, in comparison to the status quo (transport by truck in every case), about € 750.000 can be saved and the CO_2 emissions can be reduced by 50 % to about 3,450,000 tons per year. These numbers show the economic impact of the calculation since emissions can be significantly reduced, a relevant amount of costs can be saved, planning data such as due dates can be considered and the existing resources can be utilized in the best possible way. Furthermore, according to the calculations, the total time required for the renovation of the entire properties of the Swedish Million Programme will take up to ten years, depending on several factors, e.g. weather conditions and construction capacities. Just for logistics processes, almost three years of total transport time are required. In this context, it is necessary to increase the production capacities for both insulation materials and renovation panels.

6 CONCLUSIONS AND OUTLOOK

Manual renovation solutions will not be able to meet the Swedish needs in the future. Consequently, there is a need for smart factories that produce facade and roof panels in an automated production process that can transform buildings into zero-energy houses within a short time. Renovating the Swedish Million Programme properties can save a total of more than 40,000,000 tons of CO_2 emissions in the next decades. Thus, in order to transport the panels for thermal insulation, a transport network needs to be developed in which the strengths of the individual modes of transport can be combined in CT in order to transport them as efficiently as possible.

In this paper, using the DS process as a guideline, the creation of a transport network for the distribution of construction elements for the renovation of the properties of the Swedish Million Programme was structured and processed step by step.

The outcome of the six phases of the DS process can be summarized as follows:

1. Identification of the building stock to be renovated and the need for the construction of a smart factory connected to a functioning logistic transport network
2. Qualitative-explorative goal was achieved: the analysis of the infrastructural preconditions for the transport modes in Sweden
3. Development and design of a transport network architecture

4. Demonstration of suitability for problem solving through INDU-ZERO case studies using a calculation tool
5. Comparison is made between the recommendation of the calculation tool and a direct truck transport without supporting calculations
6. Communication due to principal conclusions, implications for research as well as for practitioners

By choosing this method, it was possible to focus on both the theoretical development of a transport network and the practical renovation of buildings. Likewise, the approach of comparison helped to examine the results of the calculation in terms of how they have an impact on strategic planning to fulfil the objective of efficient, sustainable logistical supply.

The elaboration of strengths and weaknesses of the different transport modes, as well as the collection of the remaining data basis (e.g. transport distances, emission data, infrastructure requirements, transport needs), are a comprehensive basis for the preparation of the artefact. Furthermore, the transport calculation serves as a tactical basis for decision-making by providing a recommendation for the most efficient form of distribution for entered the transport relation. Based on the determined results of the calculation, this contributes to the demand-oriented planning of the logistics for the renovation measure.

This developed artefact can be a future-oriented, fact-based support for the implementation of a sustainable transport strategy. In particular, connecting multiple cities within the network by applying Dijkstra's Algorithm covers the strategic aspect of route planning. A scientific application of the calculation can be done in a way that enables future research regarding occurring economies of scale in logistics. Furthermore, by analyzing the performance profiles of the transport modes, measures for increasing efficiency can be investigated.

In perspective, it has to be observed to what extent the weighting of the addressed parameters changes in logistics planning. However, against the background of the Europe-wide expansion and the promotion of CT, the impulse is forward-looking and can contribute to the generation of competitive advantages by shifting the transport volume from road to rail. Due to the further influence on the CO_2-eq balance of the transport services, such a decision support can become important in an economically relevant sector for practitioners.

Nevertheless, it should be mentioned that the identified challenges regarding the data basis could not be fully met. Precise information on the scheduling of transports as well as the applicable transport prices still have to be integrated into the master data. However, the transport prices used are sufficient for an initial indication. Accordingly, this calculation cannot represent a stand-alone solution for strategic route planning.

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