Industrial timber house building – levels of automation

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Abstract

Swedish industrial timber house building faces a constantly increasing housing demand. In order to respond to the demand, companies in this sector, have to improve their businesses in terms of productivity. At the same time, they need to meet customer requirements, i.e., offering flexible building solutions, thus creating a balance between productivity and flexibility. Off-site assembly of exterior walls is an essential part of the house production, and cutting down lead times at this phase hence, increases the competitiveness. If introduced in a right way, automation can contribute to a higher productivity. Thus, right levels of both physical and cognitive automation are necessary. The objective of this study is to measure the current levels of automation (LoA) within the off-site exterior wall assembly. Research design consisted of a literature study and a case study that was conducted at a Swedish company that is an engineer-to-order producer of single-family timber houses. A case study design was made according to the DYNAMO ++ framework. The framework was used in the assessment of LoA and designing flexible task allocation in many manufacturing industries, but there is a lack of knowledge on how to use this method in the industrial timber house building. The average physical and cognitive LoA of 124 identified tasks are 3 and 1 respectively. Increased physical and cognitive LoA for critical tasks would enable flexible task allocation between human operators and technology. It is believed that this type of flexibility can result in less production disturbances and higher productivity when a high variety of exterior walls is assembled.

Keywords –

Physical and cognitive levels of automation; hierarchical task analysis; exterior wall; single-family timber house; off-site assembly.

1 Introduction

Swedish industrial timber house building faces a constantly increasing housing demand. Compared to other materials, the use of wood for load-bearing structures is dominant in the Swedish single-family house production [1]. Moreover there is an increasing interest for timber load-bearing structures in multi-family house production [2]. Lately, 10 to 15 % of the total amount of houses that are built annually are timber frame multi-family houses [3]. In order to respond to the demand, companies in these industry sectors have to improve their businesses in terms of productivity. Nevertheless the balance between productivity and flexibility has to exist since many of the companies have customer oriented business strategies [4]. In such cases the type of supply chain is engineer-to-order (ETO) and the customer order enters the design phase of a supply chain [5]. Therefore, the lead time in ETO timber house building companies can be divided into three phases: design/engineering/process planning, off-site assembly and on-site assembly.

Timber house building, as a sub-division of the construction industry [6] has moved from the pure traditional on-site production towards the industrialized off-site prefabrication. [7] [8]. The level of off-site prefabrication varies depending on whether the house components, elements and/or volumes are delivered to the building site. [9] and [10] have made classification of the off-site assembly systems in this respect. Nevertheless customer oriented companies have understandably a lower level of the off-site prefabrication then the companies that offer standardized houses due to the transportation issues. Mostly non-volumetric house elements are prefabricated and delivered as such to the building site.

Off-site assembly of exterior walls is an essential part of the house production, in terms of the throughput time required. Assembly of these non-volumetric house elements is a bottleneck of the off-site prefabrication and cutting down lead times at this phase hence, increases the competitiveness of the company. One of the reasons to introduce automation as described by [11] is to increase productivity. Ironies of automation [12] have to be avoided therefore in order to reach higher productivity and maintain flexibility, it is necessary to establish right levels of both physical and cognitive automation [13]. The flexibility of the physical and cognitive task allocation between the operators and technology is needed due to the high number of variants of exterior walls that are pre-assembled. [14] developed a framework called DYNAMO ++ to measure levels of automation (LoA) and identify possible improvements in task allocation between humans and technology. There is a lack of knowledge about physical and cognitive LoA in the industrialized timber house building and currently there is no published material on these measurements. Therefore, it is of interest to put the developed framework for achieving flexible LoA into the context of industrialized timber house building.

The research question: What is the current state of levels of automation within the off-site exterior wall assembly? An additional objective is to compare the findings related to the research question to those of the previous case studies that used the same framework.

There are several delimitations of the study. Since the design variation in the case company is quite large, the research design for the data collection did not include all the types of exterior walls that are produced on the assembly line. The design variation refers to different types of siding on the outer side as well as different types of components such as windows, doors, electrical boxes and installations. In terms of the ETO supply chain lead time, the scope of the study was limited to the off-site assembly of exterior walls. The case study was done according to the part of the DYNAMO ++ framework. Therefore, the scope of the study is delimited only to the measurement phase of the framework.

Table 1. Reference scale for seven levels of physical and cognitive automation with exemplified explanations (adapted from [16])

LoA	Mechanical and Equipment (Physical)	Information and Control (Cognitive)
1	Totally manual - Totally manual work, no tools are used, only the user's own muscle power, e.g. the user's own muscle power	Totally manual - The user creates his/her own understanding for the situation, and develops his/her course of action based on his/her earlier experience and knowledge
2	Static hand tool - Manual work with support of static tool, e.g. screwdriver	Decision giving - The user gets information on what to do, or proposal on how the task can be achieved, e.g. work order
3	Flexible hand tool - Manual work with support of flexible tool, e.g. adjustable spanner	Teaching - The user gets instruction on how the task can be achieved, e.g. checklists, manuals
4	Automated hand tool - Manual work with support of automated tool, e.g. hydraulic bolt driver	Questioning - The technology question the execution, if the execution deviate from what the technology consider being suitable, e.g. verification before action
5	Static machine/workstation - Automatic work by machine that is designed for a specific task, e.g. lathe	Supervision - The technology calls for the user's attention, and direct it to the present task, e.g. alarms
6	Flexible machine/workstation - Automatic work by machine that can be reconfigured for different tasks, e.g. CNC-machine	Intervene - The technology takes over and corrects the action, if the executions deviate from what the technology considers being suitable, e.g. thermostat
7	Totally automatic - Totally automatic work, the machine solves all deviations or problems that occur. by itself, e.g. autonomous systems	Totally automatic - All information and control is handled by the technology. The user is never involved, e.g. autonomous systems

2 Theoretical background

Research on Levels of Automation (LoA), i.e. the allocation of functions or tasks between humans and technology, has been going on for more than half a century [15]. This early research focused very much on complex systems, mainly in aircrafts and traffic control. LoA in industrial applications was further developed by many authors, e.g. [16], who based their work on the automation strategy development by [17] and [18]. [19] defined 10 levels of automation, ranging from 1, i.e. human makes all the decisions and physical tasks, to 10, i.e. computer makes the decisions and the equipment carries out the task without humans being involved at all. In the DYNAMO project [16], reduced the number of LoAs to 7 and defined the reference scales according to Table 1. This reference scale is on a task level and so-far there is no methodology dealing with LoA on production systems level.

This method has been further developed into the DYNAMO++ framework [14]. The aim of the framework was to establish the accessible LoA present in the factory in order to create a range of possible LoA.

That would further enable a flexible task allocation by which production disturbances could be avoided and productivity increased when a high product variety is assembled at the factory [20]. The framework consists of twelve steps divided into four phases: pre-study, measurement, analysis and implementation [22]. Data is mainly collected in the measurement phase using three methods: value stream mapping, hierarchical task analysis, and levels of automation taxonomy.

The underlying question is why to automate, what to automate, and how to do it [17]. There is always a risk of creating a system that is too complex to manage and maintain, and too connected making everything stop in case of disturbances, and investing in sophisticated equipment that is not really needed.

3 Method/Case study

In order to answer the research question, case study was chosen for a research method. It involved several research techniques such as literature review, informal interviews with the operators working at the assembly line and video recording of the assembly process. The research design for data collection was done according to the measurement phase of the DYNAMO ++ framework.

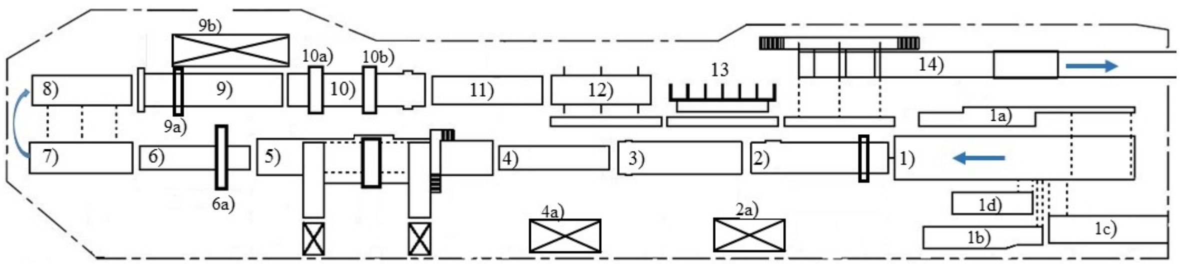

Figure 1. Assembly line layout: 1) basic wall frame assembly; 1a) horizontal studs; 1b) vertical studs; 1c) part units; 1d) rock-wool insulation; 2) wind protection sheet and air studs assembly; 2a) nailing and air studs inventory; 3) nailing studs assembly; 4) manual positioning of the horizontal siding wood panels; 4a) horizontal siding panels inventory; 5) nailing operation for vertical siding panels; 6) nailing operation for horizontal siding panels; 6a) nailing machine; 7) finalizing the outer side of the wall; 8) lifting belts assembly; 9) positioning of humidity protection plastic and gypsum/plywood boards; 9a) gypsum/plywood board positioner; 9b) gypsum/plywood board inventory; 10) nailing and routing operations for gypsum/plywood boards; 10a) nailing machine; 10b) CNC router; 11),12),13) final operations on the interior side of the wall; 14) quality control

The decision to use the DYNAMO ++ framework in this case study was based on the need to take both information and mechanical automation into consideration. A review of ten methods and models [20] that were used in redesigning, measuring or analysing production systems was used to justify the choice of the method. As the author indicated in the review, DYNAMO ++ was found to be an optimal choice where socio-cognitive and technical-physical aspects of a production system were equally taken into consideration. The other methods or models were developed for either analysis of socio-cognitive aspects:

- A model for types and levels of human interaction with automation.
- Complementary Analysis and Design of Production Tasks in Socio-technical Systems (COMPASS).
- Cognitive Reliability and Error Analysis Method (CREAM).
- Task Evaluation and analysis Methodology (TEAM)
- Taxonomy for Cognitive Work Analysis.

or technical-physical aspects of a production system:

- TUTKA production assessment tool.
- Systematic Production Analysis (SPA).
- Productivity Potential Assessment (PPA).
- Lean Customization Rapid Assessment (LCRA) [23].

The case study was conducted in the Swedish company that is an engineer-to-order producer of single-family timber houses. In terms of the level of off-site prefabrication the company pre-assembles non-volumetric house elements and does the final assembly on-site. The exterior walls are produced at the assembly line depicted in Figure 1. The assembly line consists of thirteen work stations.

The assembly of a single exterior wall was filmed with cameras. The unit of analysis was an exterior wall with windows and horizontal siding panels. This type of wall, shown in Figure 2, was chosen to be followed through the assembly process since it is the most commonly produced exterior wall at the moment and its complexity is rather intermediate.

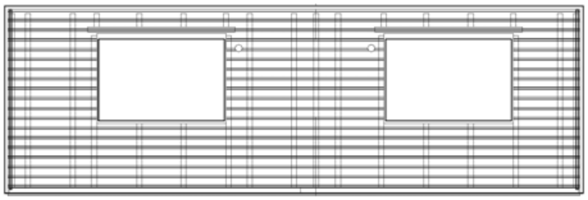

Figure 2. Part of the shop drawing of the type of wall that was followed and filmed through the assembly process

The operators working at the assembly line were given the information about the type of study and its purpose. This step was necessary for several reasons. It was important to make sure that there were no individuals who would not want to be recorded. By explaining the goals of the study operators were ensured that it is not their performance that would be assessed but rather the working tasks were under focus. This was particularly important in order to ensure that realistic current state of the work performed will be recorded. Furthermore the operators were assured that the filmed material would not be used for any other purpose other the one stated in the study objective.

The filmed material was sorted and analyzed with the purpose of developing a hierarchical task analysis map. The work stations were divided into operations/goals which were further divided into particular tasks. Every identified task was again analyzed from the video recordings and both physical and cognitive levels of automation were measured using reference scales (Table 1). For the tasks that appeared unclear in the recordings with respect to their cognitive part, i.e., which information the operators used when performing the tasks, informal interviews were conducted with several operators in order to get the full understanding of the tasks performed.

The levels of automation of all of the tasks within the assembly line were summarized according to their levels of physical and cognitive automation as shown in Figure 3. In order to put the assembly process back into the general perspective, it could be classified as either human assembling/monitoring, machine/technique monitoring or machine assembling depending on the spread of the tasks within the matrix.

A literature study was done in order to make the comparison between the exterior wall assembly and other manufacturing systems in terms of LoA. Published material from the previous case studies was analyzed to gather the data regarding measurements of LoA in other industries.

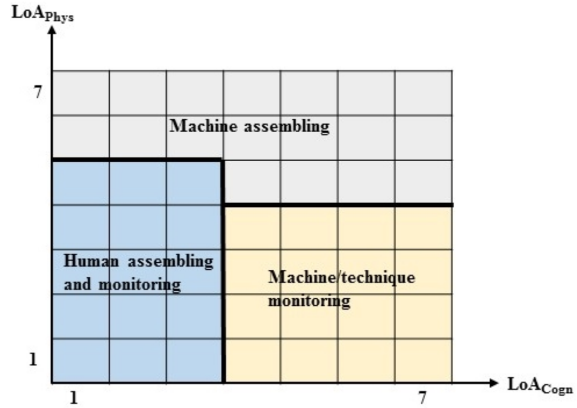

Figure 3. LoA matrix with three different regions tasks can be classified in depending on the allocation between humans and a machines (adapted from [13])

4 Findings

By implementing the hierarchical task analysis of the recorded material, 124 working tasks were identified. The working tasks are distributed over 24 operations which are further distributed over 13 working stations in the assembly line.

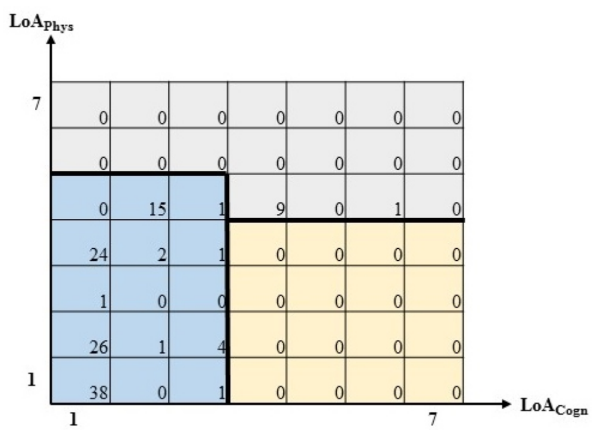

Figure 4. LoA of 124 tasks of the exterior wall assembly process

Most of the tasks, i.e., 114 out of 124, are regarded as human assembling and monitoring in terms of both physical and cognitive LoA. Aforementioned majority of tasks, the operators perform from their own knowledge and experience or using shop drawings which were the main information carriers at the assembly lines. Out of

124, 10 tasks are regarded as machine assembling. There were 9 tasks performed by the machines where information carriers were machine codes (LoA – 5:4). Only one task was performed by the machine that did not require a machine code but used sensors to take the course of the action (LoA – 5:6). Figure 4 shows a distribution of tasks according to physical and cognitive LoA.

The average physical and cognitive LoA is 3:1. The comparison between this case study and six previous studies [13] on LoA is shown in Table 2.

5 Discussion and conclusions

Some comments on research quality in terms of validity and reliability are made in the next three paragraphs. The validity of the study can be discussed from internal and external validity aspects. The internal validity, meaning as how well the researcher managed to measure and analyse what was meant to be measured and analysed, can be discussed from data collection and analysis point of view. Positioning of the cameras during the data collection had to be designed carefully in order to get all the tasks comprehensively recorded. Since the additional data collection for the missing information was done and completed through informal interviews, it can be concluded that the internal validity is quite strong in this respect. Nevertheless, the analysis of the recorded material with hierarchical task analysis and LoA measurements using LoA taxonomy, was based on researchers´ judgements and subjective feeling. It can be argued that an internal validity can be threatened in this sense.

The fact that the case study was the research method in use where a single assembly process was studied in detail, the question of the external validity, i.e., how the findings can be generalized, has to be discussed. Obviously it is not possible to apply a statistical generalization and that is sometimes regarded as a drawback of the case study research. Nonetheless, an analytical generalization can be applied, as suggested by [24]. Existing theory is expanded by adding another context to it.

Reliability of the study was insured with the fact that the data collection was done through video recordings. By having recordings as a raw data, higher reliability is achieved than if the data was collected through regular observations.

Table 2. Comparison between the case study and previous LoA measurements in other industries. ATO - assemble to order; ATS - assemble to stock

	The case company	Previous case studies					
Companies	A	B	C	D	E	F	G
Production area	House building	Engine parts	Chemistry	Electronics	Cooling modules	Trucks	Vessels
Type of assembly	Line	U-cell	Line	U-cell	Job shop	Line	U-cell
Type of assembling	ETO	ATO	ATS	ATO	ATS	ATO	ATO
Number of stations	13	4	9	5	8	5	9
Average LoA_{Phys}	3	1	5	3	1	3	1
Average LoA_{Cogn}	1	1	5	5	1	-	1

The analysis of the recordings did not only give the figures about the LoA and the HTA map, but also revealed possible issues related to some tasks. The issues are related to both mechanical and information aspects of the tasks. Considering the mechanical part of the majority of tasks, it was noted that these are mostly pick and place, i.e., totally manual tasks (LoA – 1:1). The next level is the tasks performed using simple static tools such as measuring tape or hammer (LoA – 2:1). A number of tasks included automated hand tools such as hand nailing machine (LoA – 4:1). The pick and place tasks are mainly non-value adding activities related to material handling.

Solutions with more mechanized material handling can be applied and therefore help operators to focus more on value adding activities.

Based on the observations it was noted that for some tasks there is a lack of necessary information provided to the operators. The majority of tasks the operators perform from their own knowledge and experience without using shop drawings as main information carriers. In some cases the information that is provided to the operators through shop drawings is not good enough. The real measures, the dimensions and positions, do not exactly match those specified in the instructions. The operators often need to measure themselves, calculate and get the dimensions and positions for certain components. This problem reaches far beyond the scope of the study, towards the properties and heterogeneity of wood and dimensional tolerances of the off-site assembly. Nonetheless, one can think of control/scanning systems that can provide operators correct information and that implies the higher cognitive level of automation needed.

Conclusion is that it was possible to use the DYNAMO ++ method and quantify physical and cognitive LoA of the exterior wall assembly line. Compared to the other case studies, the current LoA state in the case company is rather intermediate. The average physical LoA is intermediate while the average cognitive LoA is the lowest possible. Both physical and cognitive LoA can be increased for certain critical tasks. The increased physical and cognitive LoA would further enable the flexible task allocation between human operators and technology which is believed to be a way to enable a better production flow with shorter assembly lead time and with less production disturbances and increased productivity.

Findings and conclusions from this case study together with a value stream map (VSM), will serve as an input information for the research continuation where the rest of DYNAMO ++ framework will be carried out. The information will be used and validated in the next phase of the framework which is the workshop organized in the company. At the workshop researchers involved in the project will meet the participants from the company. The participants chosen, cover all the enterprise levels from directors and top managers to the operators working at the assembly line. The goal of the workshop is to use the results of HTA, LoA and VSM and discuss the critical tasks. The discussion about the possible improvements should lead to the LoA range specification for the critical tasks. That, in turn, would hopefully result in a future state of flexible task allocation between human operators and technology.

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