Designing proactive assembly systems –
Criteria and interaction between automation, information, and competence

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Increasing customisation of products results in decreasing production batch sizes, especially in the final assembly. Industry must therefore increase their capability to handle smaller batches as well as radically decrease set up time between different product groups and new products. This paper suggests the need for further development, primarily addressing time parameters in dynamically changing assembly systems. We propose proactivity as a vital characteristic of semi-automated assembly systems, to increase fulfilment of customer demands and decrease non value-adding tasks. In proactive assembly systems, the full and complementary potential of human operators and technical systems is utilised. Criteria for proactivity in assembly systems are reviewed from automation, information, and competence perspectives.

Keywords: Assembly systems, Automation, Information and Competence

1 INTRODUCTION

According to Frese and Fay [1], research generally focuses on reactive performance concepts, where people have to fit given tasks. Occurring needs and solutions become responses to existing problems, i.e. highly reactive actions. Often, the introduction and ramp-up of a new product is a discrete and unique event rather than a part of the assembly system long-term development. It is questionable if the reactive approach is progressive and competitive enough. Instead, assembly systems need to be dynamic and evolvable to really constitute long-term assets for the manufacturing company [2]. Consequently, the preferred assembly system would have the ability to proactively meet emergent and long-term fluctuations. In dynamic environments, the activities of the operators' job are not fixed anymore and the work situations an operator will face are unlikely to be exactly identified by work instruction sheets. Therefore, it is assumed that assembly work settings enabling proactive behaviour of the human operators will be important to handle the increasing uncertainty of work contexts [3]. The objective of the ProAct project [4] is to identify proactive solutions for time minimisation at the operational shop floor level in assembly systems [5]. The approach is based on the concept of proactivity: as the ability of operators to control a situation by taking action and effectuating changes of the work situation in advance in order to create a favourable outcome. This is in line with Griffin et al [3] who define proactivity as “the extent to which the individual takes self-directed action to anticipate or initiate change in the work system or work roles”.

In work situations characterised by uncertainty and where aspects of work roles cannot be formalised, a proactive assembly system with a focus on active participation of the operator may be favourable and is supported by several studies (see e.g. [1, 6-8]) [9].

Proactive behaviour of the operators will support both short and long range development of proactive assembly systems.

Crant describes it as; “Proactive behaviour can be a high-leverage concept rather than just another management fad, and can result in increased organisational effectiveness” [6]. A proactive behaviour is characterised by 1) anticipation of problems related to change, 2) initiations of activities that lead to solution of the change related problems and improvements in work, and 3) resolution of change related problems [10].

Regular control systems are not programmed to handle all kinds of deviation that occur in an open complex system. In addition to regular disturbance handling, proactive operators have the ability to be influenced in their decisions from clues, early warnings, uncertain information, lack of information, and overall objectives. These objectives are important since proactive operators are expected to have correct situation awareness as well as a long-term view and an anticipating perspective on the development of their work places [11]. Such a system consists of technical components efficiently integrated with human operators to constitute reliable resources in the manufacturing system. In that way, present and future requirements for productivity and sustainability by adaptability and robustness could be met [12]. The effect of predicted and unpredicted disturbances can be minimized and hereby, the availability of the entire assembly system will be increased [13]. Ideas similar to proactivity have been suggested by e.g. Endsley [18] who proposes the concept of situation awareness. By definition, human operators of complex systems can either 1) perceive, 2) comprehend, or 3) project system behaviour, thus increasing control ability and precision. Unfortunately, there is no widespread use of proactivity as a competitive factor in assembly system design. Our assumption is that proactivity is highly influenced by the respective levels of automation, information, and competence in assembly systems [12].
This paper explains criteria and interaction between these three areas (automation, information, and competence), to be able to achieve a proactive behaviour and the ability to design a competitive assembly system.

2 THEORETICAL FRAMEWORK

This section will give a brief introduction to the different areas; Levels of automation, information and competence.

2.1 Level of Automation (LoA)

There is no uncomplicated way to make automation human-oriented that is applicable across all domains and types of work. Different processes and domains may put different emphasis on precision, stability and/or speed of production. Human-centeredness is therefore a reminder of the need to consider how the system can remain in control, rather than a goal in itself. Each case requires its own considerations of which type of automation is the most appropriate, and how control can be enhanced and facilitated via a proper design of the automation involved [14]. Smart automation is defined by Ohno [15] as the human aspect of ‘autonomation’ whereby automation is achieved with a human touch. In 1951 Fitts proposed his classical list [16], where he explains how to allocate tasks between humans and machines in assembly systems. Sheridan [17] argues that if the tasks are automated in which machines are better at if the operator is required to monitor such automation while and maintaining full situation awareness1 [18] of numerous all those variables is expected, we may might lose more than we gain. Sheridan and Verplank (1978) proposed a scale of levels of automation (LOAs) involving automation of decision making and action [19]. However, automation also includes information gathering and analysis. Parasuraman, Sheridan, and Wickens [20] accordingly proposed an extension of the LOA concept to four information-processing stages: (a) information acquisition, (b) information analysis, (c) decision making, and (d) action, with each stage having its own LOA scale (for similar scales, see [21];[22]). In table 1 there is a summary of different authors defining Levels of automation. The concept Levels of Automation, used in this paper is defined by Frohm [23] as: “The allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic” By physical task Frohm [23], means the level of automation for mechanical activities, mechanical LoA while the level of cognitive task is called information LoA. Further it could be explained as; Mechanical LoA is WITH WHAT to assemble and cognitive LoA is HOW to assemble on the lower levels (1-3) and situation control on the higher level (4-7). A methodology, DYNAMO, was developed from 2004 to 2007 [23]. The aim of this method was to help companies to measure accessible LoA in order to find an appropriate span of levels of automation and, by that, maintain high productivity by reducing production disturbances [23]. The methodology was later validated in industry [24]. A further development with focus on the analysis step was done in 2008, DYNAMO++ [25]. The aim was to analyse whether the current systems’ LoA is too high, too low, or to static in order to fulfil the companies’ triggers for change e.g. internal or external demands. The DYNAMO++ methodology contains of four phases; 1) Pre study, 2) Measurement, 3) Analysis and 4) Implementation, with three steps each [25]. The first two phases are carried out in the current stage in the assembly system. The data from these two phases as well as the companies’ triggers for change are then used as input for the third phase.

Table 1 Definition of Levels of Automation

<table>
<thead>
<tr>
<th>Author</th>
<th>Definition of Levels of Automation</th>
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<tbody>
<tr>
<td>[26]</td>
<td>Divides the levels depending on who is initiating the control, the human (1-4), the human together with automation (5-8) or the automation (9-17)</td>
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<tr>
<td>[27]</td>
<td>The extent to which human energy and control over the production process are replaced by machines</td>
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<td>[28]</td>
<td>The level of automation incorporates the issue of feedback, as well as relative sharing of functions in ten stages</td>
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<td>[29]</td>
<td>Automatically is defined in six levels from conducting the tasks manually, without any physical support, to fully automated cognition with computer control</td>
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<td>[30]</td>
<td>&quot;Degree of mechanization is defined as the technical level in five different dimensions or work functions&quot;</td>
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<td>[31]</td>
<td>The level of automation goes from direct manual control to largely autonomous operation where the human role is minimal</td>
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<td>[32]</td>
<td>The level of automation in the context of expert systems in most applicable to cognitive tasks such as ability to respond to, and make decisions based on, system information</td>
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<tr>
<td>[33]</td>
<td>The level of automation is defined as the sharing between the human and the machines with different degrees of human involvement</td>
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<td>[20]</td>
<td>&quot;The interaction and task division between the human and the machine should instead be viewed as a changeable factor which can be called the level of automation&quot;</td>
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<tr>
<td>[34]</td>
<td>&quot;Level of mechanisation can be defined as the manning level, with focus on operating of the machines&quot;</td>
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<td>[35]</td>
<td>&quot;Manual&quot; tasks as being those in which humans are responsible for conducting the task (e.g. application of epoxy). Semi-automatic is a higher level of automation and involves automated alignment and application of epoxy by a robot. Material handling, on the other hand, is still conducted by humans, unlike ‘automatic’, where material handling is also automated.</td>
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<td>[36]</td>
<td>&quot;The allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic&quot;</td>
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The analysis is performed in the LoA matrix, shown in figure 1.

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1 Situational awareness is defined as: “the perceptions of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in near future.”

Figure 1 the LoA matrix
Due to the inputs, a relative min and max level for the mechanical and cognitive automation is developed and forms a Square of Possible Improvements (SoPI), illustrated in figure 2.

The square represents the task or operations’ action space in which the automation solutions for the future assembly system could vary. Depending on how the movement in this square is done, both the level of information and the level of competence are affected.

The need for cognitive support can be divided into three separate levels, developed by Rasmussen [37], i.e. Skill-, rule- and knowledge-based. At the skill-based level activities are carried out smoothly without need for conscious attention or control. Many tasks are skill-based; they are performed automatically by the operator without thinking. This relies on previous physical practice and experience. If however, the operators recognise a problem or variation between anticipated and real outcome, control moves to the rule-based level. At the rule-based level “if-then” rules stored from previous successful experience are applied. If tasks are standardised, e.g. by having tools or technique [38, 39] to give decision or teaching the operator how to perform a task the assembling becomes rule based. The applied rules can be expressed by the operators because they are aware of their cognitive activities. Yet, if there are no rules applicable to the situation, control is passed on to the knowledge-based level. In this case arguments are made from detailed analyses and there is a need for conscious and focused attention by operators. The perceived complexity of each work activity will be varying between human operators because of differences in the previous knowledge [11].

2.2 Level of Competence (LoC) and the operators role in the assembly system
ISO SS 62 40 70 [40] defines competence as “the ability and willingness to carry out a task by applying knowledge and skills”. When defining competence the following implications were made: Ability – experience, comprehension and judgment to use knowledge and skills in practice, where willingness is the attitude, commitment, courage and responsibility; knowledge means facts and methods – to know and skills is to carry out in practice – to do [5].

A list of requirements and criteria were developed by Mårtensson [41], which was based on the human needs as phrased by Maslow (1954) and the socio-technical school [42, 43]. The requirements are general and applicable to all kinds of work and consist of six areas;

- A versatile work content (e.g., the individual should plan, perform, and monitor the production task)

The list could be used as a checklist when designing the work organisation in any human – machine system and when designing a decision support for the operator of the system.

A model used for automated workplaces e.g. supervisory control was developed and is applicable primarily in the process industry [45]. The operators’ roles are; plan, teach (programming), perform, intervene and learn. These roles are described as; Plan means that the operator decides what to do in the system. The teaching step is then to transfer this plan to the system through programming but also assure that the right tools and materials are available to fulfil the plan. Monitoring means that the operator starts the process and controls the products when deviation occurs. The operator has to intervene when different disturbances occurs. The operator learns from every new task or product and can use this when planning the next batch.

The model was then further developed for the manufacturing industry by Stahre [38], also considering Rasmussen’s three levels of human behaviour; skill, role and knowledge based, as seen in figure 3.

![Figure 3 Evaluation matrix, combining supervisory control roles and human behaviour levels [38]](image-url)
The operators’ roles in this paper are a mix between Sheridan’s five operator roles and the work tasks in the automatic assembly system. Together they form a 17 point list, shown in figure 4 that is used as a reference in the case studies.

Braverman wrote in 1974: “The divorce of mental and physical work reduces, on every production level, the need of workers that are directly engaged in production because this relieves these workers from time consuming mental functions, these tasks are placed in other departments within the company” [46].

In order to create a proactive assembly system we believe that the involvement in the seventeen operator roles has to increase so that the partly or direct involvement at least is around 80%, e.g. a remarriage of the mental and physical work of the operators.

In proactive assembly systems, operators are encouraged to take more responsibility, far beyond managing operation and disturbances. Requirements on frequent reconfiguration, either initiated by explicit demands, or by changes due to proactively foreseeable problems or requirements, are normal. Correct amount, quality, an accessibility of information is required to provide the assembly system and its operators with abilities to autonomously handle changes within the assembly systems local layout and disturbances during operation. This demands a large amount of information to be exchanged in a short period if time. Moreover, the purpose is to ensure that the operator’s perspective is taken into account with respect to applicable information and future decision support systems in assembly. This means that in the future there is a need to take the operator’s abilities and limitations into consideration, as well as the operator’s various ways of using information and making decisions in different working situations [47].

2.3 Level of Information (LoI)

Information could be described as a collection of facts organised in such a way that they have additional value beyond the value of the facts themselves while an information system is a set of interrelated components that collect, manipulate and disseminate data and information and provide a feedback mechanism to meet an objective [48]. A well functional information flow throughout the chain is a powerful and necessary prerequisite [49]. A modern information system is a network of work multi-media stations, designed to present an agent with an information environment which enables the user, within the constraints posed by the work requirements to create actively a work practise that suits the individual users’ cognitive resources and subjective preferences [50].

Frequent exchange of information between different company levels is crucial to create quick “decision-loops” which are correctly connected and updated with real manufacturing conditions [11]. To perform efficiently in manufacturing, information has to fulfil different qualitative criteria like relevance, timeliness, accuracy, accessibility, comprehensiveness, and format [51].

To control the assembly work setting the operator will ask different question about the state of the system, depending on the current level of abstraction and the task. In order to be able to successfully perform the activity, the operator will usually need information from the level considered. This implies that information should represent the functional structure and state of the process [14].

Moving from a lower level of abstraction to a higher level means a change in representing system properties. However, it does not imply a removal of detailed information about the physical or material properties; rather information is added on higher level principles in
terms of describing the co-functioning of the various elements at the lower levels [14]. Consequently, the concept and structure of information representation changes at the different levels of abstraction as well as that the information appropriate to characterise the current status will be varying. Information represents the resources (material, machines, operators, etc.) available and needed for all relevant activities in order to guide operator’s activities. Moreover, operators need information about the level above and the level below. The former one is related to the immediate purpose of the control decision, i.e. why it is made, while the latter one represents how a decision can be implemented [14]. The abstraction hierarchy implies that for each task the questions of why, what and how need to be answered (figure 6).

3 Criteria and interaction between LoA, LoC and LoI

The socio-technical school [42, 43] is based on the relation between the social system which could be tied to the Level of Competence (LoC), Level of Information (LoI) and the cognitive Level of Automation (LoA). The technical system could be connected to mechanical LoA and in some cases LoL.

To achieve the goal function, a proactive behaviour, we believe in a reduction in different time parameters e.g. set-up time, MTBF, cycle-time, throughput time and non value adding time [11, 53], in the current system. This could be done by understanding the interaction between the level of automation, information and competence and then change these three areas.

The ProAct loop illustrated in figure 7 is an illustration of a Meta methodology, connecting the three areas by using different methods with situation awareness as a central point.

Figure 7 the ProAct Loop

The loop is used in two stages, the first stage is to investigate and map the current system in all three areas:

DYNAMO++, LoA
- Pre study phase
- Measurement phase

Competence analysis, LoC
- Competence matrix for the different tasks, related to Skill-, rule- and knowledge-based human behaviour levels
- The number of beginner-, normal- and expert operators in the operator group.
- The percentage of fully-, partly- or non involvement of the operators in the 17 point, shown in figure 4.

Analysis of information needed, LoI
- Minimum information needed for the operator group to be able to plan and assemble quality products e.g. Batch sizes, due dates etc.
- Relevance, timeliness, accuracy, accessibility, comprehensiveness, and format of the information presented
- Information shown and needed for the operation group in the different abstraction levels, illustrated in figure 6
- Information needed connected to three competence levels; beginner-, normal- and expert operators.

The second stage or loop, future stage, is used for a) analysing the triggers for change (e.g. internal or external demands) and the ability to reach or improve the proactive behaviour in the assembly system. The data collected from the first loop is used as input. The first method, to put the data into, is the DYNAMO+++ methodology, in the analysis phase. The result is a square of possible improvements (SoPI), with both physical and cognitive automation possibilities.
The two levels of possible improvements are on single task level and operational level (figure 8).

Figure 8 Task and operation optimisation [54]

The span of different automation solutions contribute with a larger span of possible solutions for replacement and in real time optimisation. Equipment for automation for mechanical, cognitive tasks and information tools can be evaluated with the criteria anticipation, initiations of activities and resolution of change-related problems. The criteria support correct situation awareness for the operator team. This put requirements on the information to have ability to both provide correct information about the system, the resources and the system as a whole e.g. from higher abstraction levels, illustrated in figure 9. Information also needs to be presented it in a way that supports the operator team to have the correct situation awareness in a short time.

Figure 9 Time perspective in the Why, What, How matrix

The competence of the operator team is crucial because this realises the system’s proactivity that is built in. Competence is not replaceable with information but it could be reinforced with the right level of information. Without correct competence it’s not possible to have correct situation awareness in a short time. The competence is the ability to do the right action and also to predict the consequences of the action taken. The operator has to have a competence within the group to be “aware of the environment within a volume of time and space, and to understand their meaning and the assembly systems status in near time and in the future”.

Through proper application of the ProAct development cycle, the system operators’ ability to perform in their roles may be radically increased. Their situation awareness is increased and thus their ability to act proactively. Continuous iterative development of the system design increases usability from a physical and a cognitive perspective. Through cyclic development of the physical and cognitive user interfaces the operators may refocus their energy from comprehension of the process to problem-solving, projection of system behaviour, and refining of the system.

5 CONCLUSION

The paper has described the criteria and interaction between the three areas; automation, information and competence in order to design a proactive assembly system. Furthermore a Meta-method, the ProAct-loop, which could be used to design future proactive assembly system, has been showed.

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