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ARTICLE · JANUARY 2008

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ABSTRACT

The objective of this paper is to explore the concept "Levels of Automation" (LoA). The paper presents a literature review on definitions and taxonomies for LoA across multiple scientific and industrial domains. A synthesizing concept is suggested, including a LoA definition and taxonomy aimed at application in the manufacturing domain. Results suggest that the level of automation should be divided in two separate variables, i.e. physical/mechanical LoA and cognitive/information-related LoA. Further, that LoA in a manufacturing context can be described and assessed using 7-step reference scales for the physical and cognitive LoA respectively.

Key words: Manufacturing, automation, allocation, taxonomy

1 INTRODUCTION

Highly automated product realization has been an important mean for industry to meet the competition from low-cost countries, primarily due to relative high wage cost observed in e.g. the US and in Europe (Kilbo 2001; Teknisk framsyn 2000). Throughout the 20th century, extensive efforts to develop automated production processes where used by manufacturing companies to radically increase efficiency and sustain a high quality of production. Increased automation was not only concerned with actual manufacturing processes, but also focused on supporting tasks (e.g. material handling, transport and storage) (Reveliotis 1999). However, even if there were ambitions during the 1980's even to create so-called "lights-out factories" with full automation in each production unit (Mital 1997), most automated systems within manufacturing are still semi-automatic with manufacturing systems consisting of combinations of automated and manual tasks. This is especially apparent within assembly operations, which have generally been more difficult to automate at a justifiable cost (Boothroyd 2005).

In addition, product customization demands and increased product complexity have resulted in increasingly complex manufacturing systems as well as increased levels and extent of automation (Satchell 1998). However, neither automation to fulfill efficiency requirements, nor automation to achieve flexibility does necessarily lead to expected results (Youtie et al. 2004). In fact, excessive levels of automation (LoA) may result in poor system performance (Endsley 1997; Endsley and Kiris 1995; Parasuraman et al. 2000). Further, complex manufacturing systems are generally vulnerable to disturbances, which might lead to possible overall equipment efficiency (OEE) degradation (Ylipää 2000). In parallel, degraded operator performance may be caused by e.g. lack of knowledge, gradual loss of special working skills, degradation of situation awareness (Endsley 1997; Endsley and Kiris 1995; Parasuraman et al. 2000), or unexpected increase in cognitive workload (Connors 1998)

Consequently, the human actor is usually a component in the manufacturing system, and as such, she has to be involved in the technical advancements and needs to be able to handle machines and equipment. In other words, both advanced technical system and skilled human workers are necessary for achieving flexible and efficient manufacturing. Thus, automation decisions are not trivial; indicating a need for a deeper understanding of automation as well as the way automation is approached by manufacturing industry as well as manufacturing research.

The objective of this paper is to increase understanding of task allocation within semi-automated systems and to provide a systematic approach for changing the level of automation. Our approach towards this goal is to:

- Review Level of Automation (LoA) definitions and taxonomies
- Suggest a LoA definition and taxonomy for use in manufacturing

Research presented is part of a Swedish research project named DYNAMO - Dynamic Levels of Automation. This was a three-year project, ending in 2006, initiated to address industrial needs for adaptive solutions and dynamic change in automation levels in manufacturing systems during different phases of the system life cycle. The project aimed to provide industry with design, measurement, visualization, and management tools for dynamic levels of automation in manufacturing.

2 RESEARCH APPROACH

The paper focuses on level of automation taxonomies at an operative level, i.e. allocation and distribution of tasks between human operators and technical subsystems. The results presented in this paper are based on key publications in the areas advanced manufacturing technologies (AMT), human factors, and teleoperations. The review concludes with a definition and taxonomy of LoA to be used in manufacturing. The taxonomy was developed through case studies in manufacturing environments in relation to the literature review. Finally, the proposed LoA taxonomy is visualized through a generalized example in a manufacturing context, based on the empirical findings from the case studies. The literature search was carried out by means of Science Direct, Compendex, Inspec, IEEE Xplore, Ergonomics Abstract, and Google Scholar. Keywords used were e.g. levels, automation, degree of, task, allocation, control, information process, production, and manufacturing.

3 WHAT IS AUTOMATION?

One difficulty in defining automation lies in the multitude of context-specific definitions available. The Oxfords English Dictionary (2006) defines automation as:

> *Automatic control of the manufacture of a product through a number of successive stages; the application of automatic control to any branch of industry or science; by extension, the use of electronic or mechanical devices to replace human labor*

As seen in this definition, automation often refers to the mechanization and integration of the sensing of environmental variables. With the emergence and rapid growth of information technology, the relevance of systems, which integrate information technology and mechanical technology, increases (Satchell 1998). Today, the term automation has grown beyond manufacturing, which was the popular context of historical automation implementation. However, with emerging concepts like 'knowledge workers' (Drucker 1999), human work practices have gone from physical labor, to also covering cognitive labor. Today we use computers to interpret and record data, make decisions, and visualize information. Such tasks are regarded as automation, including the sensors that go with them. Therefore, in industrial sectors where human capability is important to safety, e.g. airplanes, user-centered approaches to automation have evolved and thus different degrees of human cognitive process that are in touch with machines (Billings 1997). Recently, other definitions of human-machine integrations have emerged (Satchell 1998), focusing on sharing of tasks, control, and authority between human and machines, regarding the two as being mutually complimentary. A central question for designing automation within manufacturing systems has therefore not only been how to design the best system, but also how to optimize the Task Allocation (TA) between human and automation.

3.1 Task allocation

Initial contributions to the field of task allocation were made by Fitts (1951), who presented a list of general tasks covering both humans and machines, illustrating where the performance of one category exceeds that of the other (table 1).

Table 1 Fitts' List, in (Hoffman et al. 2002)

HUMANS SURPASS MACHINES IN THE:	MACHINES SURPASS HUMANS IN THE:
▪ Ability to detecting small amounts of visual or acoustic energy ▪ Ability to perceiving patterns of light or sound ▪ Ability to improvise and use flexible procedures ▪ Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time ▪ Ability to reason inductively ▪ Ability to exercise judgment	▪ Ability to respond quickly to control signals, and to apply great force smoothly and precisely ▪ Ability to perform repetitive, routine tasks ▪ Ability to store information briefly and then to erase it completely ▪ Ability to reason deductively, including computational ability ▪ Ability to handle highly complex operations, i.e., to do many different things at once.

However, since its introduction, a range of criticism has arisen regarding the applicability of Fitts' list in systems engineering. Jordan (1963), for instance, stated that the attempt to compare the abilities of human and machines is inappropriate since only machines can be designed for a specific pre-defined task. According to Jordan, the idea of comparing human and technology should there for be discarded, yet system designers also should keep in mind what humans and machines do best, and embrace that the two are complimentary rather than conflicting entities when designing a human-machine system. In order to make use of ideas of Jordan, Price (1985) represents the allocation of tasks in a decision space, in which the x-axis represents the 'goodness of humans', scaled from unsatisfactory to excellent, and the same for the machine on the y-axis (figure 1).

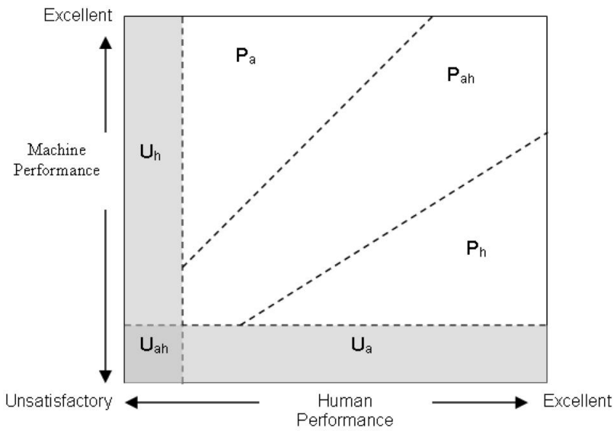

Fig. 1 Decision matrix for allocation of functions (Price 1985)

In line with Fitts' notation, as can be seen in figure 1, some tasks have to be allocated to the machine (U_h) or to the human (U_a) for reasons such as physical strength or demands for problem solving. There are also tasks that both human and automation are qualified to handle (P_a, P_h and P_{ah} in figure 1). It can be noted that tasks that do not need to be solely allocated to human or to the automation, are tasks where the human or the automated system need support from each other.

As mentioned in Fitts' List, decisions on task allocation between human and technology (e.g. within the manufacturing system) can be based on different factors and criteria (Frohm et al. 2003). For example, according to the Purdue Enterprise Integration Reference Architecture suggested by Williams (1999), task allocation can be based on e.g. financial, technical, or social factors. These factors can in turn be organized into three categories of implemented tasks or business processes according to Williams:

- All direct mission enabling elements of the enterprise (that is, all of the equipment providing the product and/or service functions which comprise the mission to the customers of the enterprise),
- All control and information function enabling elements (equipment again), and
- All humans involved in the enterprise (humans may serve along with the equipment in either the direct mission enabling functions and/or the control and information functions, which monitor and control the mission elements).

According to Williams (1999), only two of these classes of tasks have to be considered when the functionality is in focus (operating the 'processes' and 'control' the mission in an 'optimal' manner), but there are three classes of implementation, since humans may be asked to implement any of the tasks from either functional class (figure 2).

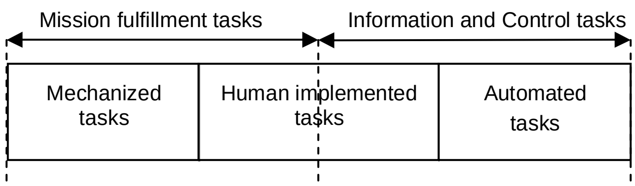

Fig. 2 Human implemented tasks may be classified either as mission fulfillment task or as information and control task, based on the PURDUE Architecture for Manufacturing Systems (PERA). (Williams 1999)

To make a manufacturing system as robust and flexible as possible is consequently in line with Billings (1997) and Sheridan (2002) not only a question on how to assign the right task and function to the right element of the system. It is also a question on how the human and automated elements can support eachother during different levels of automation, to make the manufacturing system as robust and flexible as possible.

4 THE LEVEL OF AUTOMATION CONCEPT

It is often the case that progression from manual operations to full automation is said to be made in one single step, i.e. when the operators are replaced by robots or advanced machinery. This is however not completely true. According to Encyclopedia Britannica (2006), manual operations are defined as "work by hand and not by machine", and machines are in the same way defined as "instruments (e.g. a lever) designed to transmit or to modify the application of power, force, or motion". The term manual can thereby be defined as work performed without any tool or support. Thus, giving the user tools or other support to achieve the task can be seen as increasing the level of automation and approaching full automation. Another example is a bolt that can be fitted into a construction by hand, which may be seen as the lowest level of manual work. However, by supplying the operator with manual or automated hand tools (e.g. spanner or hydraulic bolt machine) the level of technological support is raised. By further replacing the electrical or hydraulic hand tool with a machine or robot on the workshop floor, we reach almost full automation.

Even if the example may seem trivial, it can be noted from literature that the concept of "level of automation" (LoA) has been considered by many authors (see table 2) from areas such as aviation, telerobotics, and process industry. From the review in this paper, it can be seen that the simplest form of automation often operates in two modes, manual or automatic. However, within more complex systems, e.g. aviation, control rooms within nuclear power plants and within manufacturing, it is not uncommon to find multiple automation modes of both physical as control and information support.

Table 2 A selection of level of automation definitions

Author	Levels of Automation definition
Amber and Amber (1962)	The extent to which human energy and control over the production process are replaced by machines.
Sheridan (1980)	The level of automation incorporates the issue of feedback, as well as relative sharing of functions in ten stages.
Kern and Schumann (1985)	Degree of mechanization is defined as the technical level in five different dimensions or work functions.
Billings (1997)	The level of automation goes from direct manual control to largely autonomous operation where the human role is minimal.
Endsley (1997)	The level of automation in the context of expert systems is most applicable to cognitive tasks such as ability to respond to, and make decisions based on, system information.
Satchell (1998)	The level of automation is defined as the sharing between the human and machines with different degrees of human involvement.
Parasuraman *et al.* (2000)	Level of automation is a continuum from manual to fully automatic operations.
Groover (2001)	The level of automation can be defined as an amount of the manning level with focus around the machines, which can be either manually operated, semi-automated, or fully automated.

As indicated in table 2, levels of automation are quite well covered within area of human factors. There are, however, only a few publications of LoA within the manufacturing area. From the manufacturing perspective, LoA has often been seen in line with Groover (2001) as the manning level, i.e. a comparison between the actual numbers of operators on the workshop floor in relation to the number of machines.

Based on our review, it can be noted that automation is not all or nothing, but should rather be seen as a continuum of automation levels, from the lowest level of fully manual performance (based on the capabilities of the human) to the highest level of full automation (without any human involvement).

Also, based on the literature review, it can be argued that automation can vary across different levels, and exists as a continuum of full, partial, or no replacement of a function previously carried out by the human operator.

4.1 Taxonomies for the Level of Automation concept

Based on the review in this paper, can it be argued that the level of automation concept should be described in more depth. In previous case studies (Frohm et al. 2005; Lindström et al. 2005), it was observed that most automated processes within manufacturing in the beginning seem to only involve automation of mechanical tasks. However, those tasks are mostly controlled by computers for optimal performance (Frohm et al. 2005).

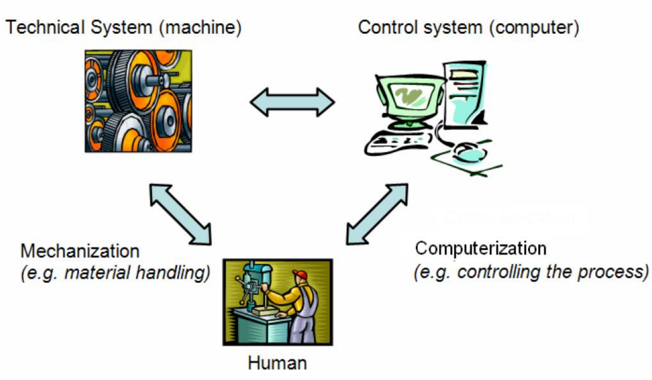

Fig. 3 Separation of functions into mechanization and computerization (Frohm et al. 2005)

It is therefore important to recognize that automation in manufacturing can be seen in line with Chiantella (1982) and Williams (1999) as two basic classes of automation, *mechanization* and *computerization* (figure 3). Computerization is defined in this paper as the replacement of cognitive tasks, such as human sensory processes and mental activity. This would include e.g. collection, storage, analysis, and use of information in order to control the manufacturing process. Mechanization is in a similar way connected to computerization and is defined as the replacement of human muscle power, such as material and energy transformation (Frohm et al. 2005).

4.1.1 Mechanization - automation of physical tasks

Mechanization as such is often associated with individual manufacturing machines and robots (Allum 1998; Bright 1958; Duncheon 2002; Groover 2001; Kern and Schumann 1985). Further, the concept of automated systems can also in line with ISO, be applied to various levels of factory operations (Gullander 1999), since manufacturing machines are made up of subsystems, which can each be automated individually. One example of this is the Computerized Numerical Control (CNC) machine, which is composed of numerous integrated and automated subsystems. The CNC-machine may further be integrated with automated transportation systems, thus forming an automated group of manufacturing equipment (a manufacturing system), which in itself may be part of a highly automated manufacturing plant.

For example Kern and Schumann (1985) suggested that the 'level of mechanization' can be defined as the technical level of the manufacturing system. As seen in table 3, the 'level of mechanization' can be classified into pre-mechanization, mechanization, and automation. These three categories can be further divided into nine steps, ranging from manual to automated manufacturing.

Table 3 Three levels of mechanization, adopted from (Kern and Schumann 1985)

Pre-mechanization	Manual
	Line flow
Mechanization	Single units with manual work
	Single units with mechanical control
	Multi-functional units without manual control
	Systems of units
Automation	Partly automated single units
	Partly automated systems
	Automated manufacturing

In similarity to Kern & Schumann, Groover (2001) suggests that the term 'level of mechanization' can be defined as the manning level, with focus on operating of the machines. According to Groover, the level of automation can be either operated *manually*, *semi-automatically*, or *fully automatically*.

Also Duncheon (2002) suggests, in the context of fiber optic component assembly, that the 'level of automation' can be visualized in three main automation levels (table 4).

Table 4 Three levels of mechanization (Duncheon 2002)

Manual	
Semi-automatic	Automated alignment
	Automated process
	Automated cassettes
Automatic	Robotic material handling
	Automated inter-cell transfer

As indicated in table 4, Duncheon (2002) defines in a similar way as Kern & Schumann (1985); 'manual' as tasks were the humans are responsible for conducting the task (e.g. application of epoxy). 'Semi-automatic' is a higher level of automation and involves, according to Duncheon, automated alignment and application of epoxy by a robot. Material handling, on the other hand, is still conducted by humans unlike 'automatic', where also material handling is automated.

Based on the three previous taxonomies, it can be presumed that the level of automation or mechanization can be seen as three levels, from manual to fully automated manufacturing. However, most manufacturing systems consist of both humans and automation in connection. This means that most tasks are falling between manual and full automation.

From a generic manufacturing strategy perspective, Chiantella in Kotha and Orne (1989) presented a model of process complexity, where the 'level of automation' consists of mechanization (physical tasks) and systemization (control of the physical tasks). Here in chapter 4.1.1, only the physical (mechanization) part of LoA will be addressed. As seen in table 5, Chiantella (1989) classifies mechanization in four levels, and emphasizes similar to Duncheon (2002) that 'manual' tasks can involve operations with a minimum of tools. In line with previous taxonomies, it can be seen that the 'level of automation' increases as more tasks are being carried out automatically.

Table 5 Four levels of mechanization (Kotha and Orne 1989)

Manual	A human operator performs an operation manually with a minimum of tools. Component assembly using simple fixtures and hard tools would be an example
Machine	The operator employs mechanical assistance in performing an operation, as in the fabrication of parts using milling machines, lathes or presses
Fixed program	A fixed program machine may employ pneumatic logic, mechanical sequencing or numerical control to execute a sequence of operations. No provision are made for exceptions to the normal process
Programmable control	Under programmable control a machine may execute a sequence of operations and compensate for exceptions that may occur. A machine may be programmed to perform different tasks as well.

As previously stated, automation often relates to allocation of physical tasks, i.e. those functions that according to Williams (1999) are involved in operating the processes which results in making the 'product'. However, for some time focus of automation efforts has been extended to address control tasks such as supervision, problem solving etc. Therefore, it seems to be appropriate to separate the level of automation into a) physical tasks, such as manufacturing technologies, and b) control tasks such as supervision and problem solving.

4.1.2 Computerization – automation of control and information handling

Based on previous case studies (Frohm et al. 2005; Lindström et al. 2005) can it be argued that computers are often implemented into many modern manufacturing operations for optimal performance control. Furthermore, recent literature, e.g. Mital and Pennathur (2004) concerning research related to humans in advanced, dynamic and automated systems (e.g. remote controlled machines and robotics), has presented a number of taxonomies of level of automation. In the same way as regarding mechanized task performance, most taxonomies on the computerized and information/control-oriented side also offer intermediary levels of automation between fully manual control and full automation. These levels are, according to Kaber et al. (2000), intended to maintain both human and computer involved in active system control, and thereby improving the operators understanding and awareness of the present and future situations (Endsley 1997). From literature, it can be seen that there are mainly two ways of looking at levels of computerization. The first is the classical ten-level taxonomy suggested by Sheridan and Verplanck (Sheridan 1980) focused on human-computer decision making in the context of undersea teleoperation systems (table 6).

Table 6 The Sheridan-Verplanck 10 levels of automation (Sheridan 1980)

1. Human considers alternatives, makes and implements decision.
2. Computer offers a set of alternatives which human may ignore in making decision.
3. Computer offers a restricted set of alternatives, and human decides which to implement.
4. Computer offers a restricted set of alternatives and suggests one, but human still makes and implements final decision.
5. Computer offers a restricted set of alternatives and suggests one, which it will implement if human approve.
6. Computer makes decision but gives human option to veto prior to implementation.
7. Computer makes and implements decision, but must inform human after the fact.
8. Computer makes and implements decision, and informs human only if asked to.
9. Computer makes and implements decision, and informs human only if it feels this is warranted.
10. Computer makes and implements decision if it feels it should, and informs human only if it feels this is warranted.

As seen in table 6, Sheridan and Verplanck's taxonomy incorporates issues of feedback as well as the relative sharing of functions, determining options, selecting options, and implementing tasks between the human and the technical system. This taxonomy is also one of the most descriptive taxonomies that can be found in literature in terms of identification of 'what' the operator (human) and the technical system (computer for information and control) are to do under different LoAs, and 'how' they should cooperate. Also Satchell (1998) stresses that sharing between humans and machines can occur in many forms, and these forms can be stratified into different levels depending on the degree of human involvement. Inagaki (2003) further develops task allocation methods, introducing not only sharing but also trading of control.

The other way of viewing levels of computerization is from a perspective of human information processing (Wickens and Hollands 2000), which determines that human information processing consists of the following four steps: acquire the information, analyze and display the information, decide action based on the analysis, and finally implement the action based on the decision (Parasuraman, 2000). As mentioned in the previous chapter, Chiantella model of process complexity also includes systemization in Kotha and Orne (1989), which is employed to control a process. Chiantella describes the level of systemization in six levels ranging from collecting data from the process, which involves acquiring information, to closing the control loop by feedback the information and using the collected data directly into the manufacturing process.

Table 7 Levels of systemization according to Chiantella in (Kotha and Orne 1989)

Data collecting	Recording past occurrences – documents (reports) produced at some later time
Event reporting	Capturing information as event occur – documents are produced when and where required
Tracking	A continuing profile of event information for a series of operations or movements
Monitoring	Dynamically comparing actual events to those planned. Alert messages are produced
Guide	Providing action alternatives, and capturing the course of action taken
Control	Executing a control action when predefined event conditions occur.

As shown by e.g. Parasuraman (2000), the tasks at each of these four stages can be automated to different degrees or levels. By combining the Sheridan-Verplank taxonomy with the model of human information processing, Parasuraman showed that a particular system could involve automation in all four dimensions at different levels. For example, a given system A (black line in figure 4) could be designed to have moderate to high level of acquisition (level 5-7), low level in analysis and decision selection (level 2-3), but high in implementation (level 6-8). Another system B (gray line) on the other hand, might have high levels of automation across all four stages.

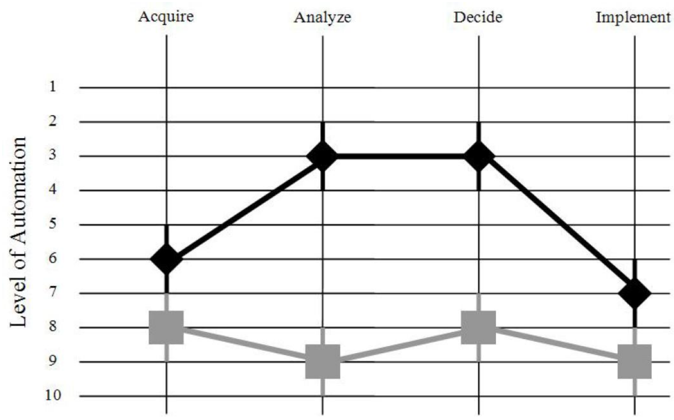

Fig. 4 Examples of different levels of automation at different task stages (Parasuraman, et al. 2000)

Endsley and Kaber (1999) presented a taxonomy that could give support to the human by means of expert systems, which where developed for e.g. air traffic control, advanced manufacturing, and teleoperations. Endsley (1997) had previously proposed that there are five functions in a human-machine system that either human or an expert system can perform: *suggest*, *concur*, *veto*, *decide*, and *act*. By structuring those five functions to serve the full range between *manual* and *full automation*, Endsley and Kaber (1999) suggested a ten level taxonomy for wider applicability to a range of cognitive and psychomotor tasks requiring real-time control, see Table 8.

Table 8 Five levels of automation (Endsley and Kaber 1999)

Level of automation	Roles			
	Monitoring	Generating	Selecting	Implementing
(1) Manual control	Human	Human	Human	Human
(2) Action support	Human/computer	Human	Human	Human/computer
(3) Batch processing	Human/computer	Human	Human	Computer
(4) Shared control	Human/computer	Human/computer	Human	Human/computer
(5) Decision support	Human/computer	Human/computer	Human	Computer
(6) Blended decision-making	Human/computer	Human/computer	Human/computer	Computer
(7) Rigid system	Human/computer	Computer	Human	Computer
(8) Automated decision-making	Human/computer	Human/computer	Computer	Computer
(9) Supervisory Control	Human/computer	Computer	Computer	Computer
(10) Full Automation	Computer	Computer	Computer	Computer

In comparison to the models of Endsley and Kaber (1999) and Parasuraman (2000), the Lorenz et al. (2001) model concluded that automated systems do not only differ as a function depending on LoA, but also on different types of automation, corresponding to which of the four information-processing stages (monitoring, generating, selecting, and implementing) that are supported by automation. Lorenz et al. (2001) instead proposed that LoA could be seen through four stages of automation (table 9).

Table 9 Four levels of automation (Lorenz et al. 2001)

Absence of automation	No support is given
Notification	The system provided information about what happened, and assists the operator in his or her decision-making
Suggestion	The system notified and suggested the appropriate action to take, but leave the operator to decide and to act
Action	The system resolved the problem by itself and informs the human to allow him or her to veto

Another way of describing LoA, according to Billings (1997), is to see LoA not as a single progression from total manual control to fully automated control, but as a parallel control—management continuum. Applied on air-traffic controllers, this would mean ranging from unassisted control to autonomous operations in six levels (table 10).

Table 10 Continuums of control and management for air-traffic controllers (Billings 1997)

AUTOMATION FUNCTION	MANAGEMENT MODE	HUMAN FUNCTION
Fully autonomous operation; Controller not usually informed. System may or may not be capable of being by passed	**Autonomous operations**	Controller has no active role in operation. Monitoring is limited to fault detection. Goals are self-defined; pilot normally has no reason to intervene.
Essentially autonomous operation. Automatic decision selection. System informs controller and monitors responses.	**Management by exception**	Controller is informed of system intent; May intervene by reverting to lower level.
Decisions are made by automation. Controller must assent to decisions before implementation.	**Management by consent**	Controller must consent to decisions. Controller may select alternative decision option
Automation takes action only as directed by controller. Level of assistance is selectable.	**Management by delegation**	Controller specifies strategy and may specify level of computer authority.
Control automation is not available. Processed radar imagery is available. Backup computer data is available.	**Assisted control**	Direct authority over decisions; Voice control and coordination.
Complete computer failure; No assistance is available	**Unassisted control**	Procedural control of all traffic. Unaided decision-making; Voice communication.

Even if Billings (1997) indicated that the levels of automation are a division of tasks between the human and the automated system, the important point is that the role of the operator can vary. It can e.g. go from direct authority over the entire manufacturing process to a relatively passive surveillance function, in which the operator control task is handled by the technical system. From areas such as aviation, nuclear power plants, and advanced manufacturing systems, it can be noted that none of them today can be operated entirely at either end of this spectrum of control and management. Indeed, complex systems such as airplanes or advanced manufacturing systems can be under direct manual control, while still incorporating several kinds of control automation. Even remotely controlled systems (e.g. NASA's Mars explorer) are not fully autonomous in the sense that the locus of control of such systems simply has been relocated. Similar to Billings (1997), Ruff et al. (2002) describe a context-specific LoA for remotely operated vehicles, or unmanned air vehicles (table 11), which is based on the taxonomy by Rouse and Rouse (1983) and corresponds to Sheridan's level 1, 5 and 6.

Table 11 Three levels of automation (Ruff et al. 2002)

Manual control	– Automation is dormant until initiated by operator – Manual control is the 3 situation where automation is dormant unless initiated
Management-by-consent	– Automation proposes action, but cannot act without explicit operator consent – Management-by-consent is the situation where automation proposes action, but cannot act without explicit operator consent.
Management-by-exception	– Automation acts without explicit operator consent, requiring specific commands from the operator to cancel automation – Management-by-exception is the situation where automation acts without explicit operator consent and only fails to act when explicitly commanded by the operator

A further development of LoA in the context of Telerobotics control was developed by Milgram et al. (1995), see table 12, who defined LoA by considering the different roles a human operator can play in controlling telerobotics, including being a decision-maker and direct controller. As Milgram et al. point out; one of the key aspects that have to be considered is the role of the human operator in relation to other elements of the control system. This means that, for anything other than completely automated systems, it will resolve into a spectrum of different tasks for the human operator, ranging from *manual teleportation* to *autonomous robotics*.

Table 12 Five levels of automation (Milgram et al. 1995)

Manual Teleoperation	The most basic operating mode, defines all situations in which the human operator is constrained to remain continuously in the control loop.
Telepresence	Typically, this involves some form of master-slave control system, where the human operator initiates all actions of the master arm.
Director / Agent Control	Director / Agent (D/A) control can be considered as a basic form of supervisory control, where the human operator acts as a director and the limited intelligence robot acts as her or his agent.
Supervisory Control	Supervisory control describes a wide range of options were the human operator can take on a variety of supervisory roles.
Autonomous Robotics	Fully autonomous teleoperations. The system work without remote control and the human has no part in controlling the system.

Also Draper (1995) discusses the level of control and how to combine human operators with machine control in the context of teleoperations, see Table 13. Similar to Endsley (1997) Draper identified five different functions (programming, teaching, controlling, commanding and monitoring), that has to be carried out by the human. In relation to the human function, Draper also identified four functions (controlling, modifying, communication, and displaying) that have to be allocated to the machine.

Table 13 Five levels of automation (Draper 1995)

Human control	Total human control
Manual Control with Intelligent Assistance	Human control and teaching with machine modification of control inputs.
Shared Control	Human control and monitoring and machine control of (routine) subtasks.
Traded Control	This level involves consecutive assignment of subtask control to the human and machine depending on the characteristics of the task and server capability.
Strategic control	Involving human long-term operations planning accompanied by machine performance of tasks.

Based on that allocation of tasks, Draper proposed five levels of automation, ranging from human control to strategic control involving human long-term operations planning, accompanied by machine performance of tasks (table 13). Also Anderson (1996) presents a similar context-specific LoA approach as Draper (1995) and Milgram et al. (1995), for telerobots in three levels (table 14).

Table 14 Three levels of automation (Anderson 1996)

Autonomous Control	An operator programs a series of points that a robot is to move to in order to perform manipulative functions.
Direct Teleoperation	An operator is required to directly command all activities of the robot in real-time, using a hand-pilot instead of programming.
Shared Control	The robotic system involves a blend of the characteristics of these two modes including superimposing inputs of the operator and computer control on each other.

Similar to Draper, Schwartz et al. (1996) identified that there are five different tasks that users have to carry out to some extent in the context of teleoperations of satellites. From the assignment of those five tasks, Schwartz identifies six levels of automation (table 15), ranging from *no automation* to *fully automated* operation.

Table 15 Six levels of automation (Schwartz et al. 1996)

No Automation	Satellite downlinks raw telemetry data to ground. A human controller then performs the function without any filtering or processing.
Data Filtering	Satellite downlinks raw telemetry data to ground. Ground segment then filters and processes the data and a human controller performs the function.
Cueing	Satellite performs function and suggests possible solutions. Ground segment must verify all solutions (using filtered data) before they can be implemented.
Supervision	Satellite performs function but ground segment supervises recovery activities. Ground is aware of the satellite's progress (through filtered data from the satellite) and can override any actions, but is not required to intervene unless stall occurs.
Paging	Satellite performs function but ground segment notified if processor stalls. In such a case, ground controller then resolves problem-using data filtered from the satellite.
Fully Automated	Satellite performs function with no communication to ground. No ability to recover if satellite processor stalls.

Based on the presented taxonomies for automation of control and information, it can be argued that many of the presented taxonomies are designed for specific predefined tasks, and thereby might have limited applicability in other systems such as manufacturing. It has also been noted by Kaber et al. (2000) that taxonomies of LoA that are designed for specific tasks might result in a reduction of the human operators' understanding of the automated systems during an automation failure. Bainbridge (1982) already foresaw this conclusion in her classical statements on the ironies of automation.

4.1.3 LoA in Manufacturing

In previous case studies (Frohm et al. 2005; Lindström et al. 2005) the authors of this paper have observed that most tasks within modern manufacturing seem to involve a mix of both mechanization and computerization. Further, that observed tasks and operations could be broken down into *mechanized* and *computerized* activities. For example, to operate a cutting machine, tasks such as controlling the cutting tool (computerized activity) as well as handling the work pieces and performing the cutting (mechanized activity) are involved.

We now propose that a selection of taxonomies for mechanization and computerization reviewed by this paper can be assembled in a way that makes them relevant for the manufacturing field.

The idea to combine automation of physical tasks with control tasks is not new. In 1958, when automation introduced a new manufacturing era, Bright (1958) described and presented a concept of mechanization profile, consisting of 17 levels of mechanization, see Table 16.

Table 16 Levels of mechanization (Bright 1958)

Initiating Control Source	Type of Machine Response		Power Source		LEVEL OF MECHANIZATION
From a variable in the environment	Responds with action	Modifies own action over a wide range of variation	Mechanical (No-manual)	17	Anticipates action required and adjusts to provide it.
				16	Corrects performance while operating
				15	Corrects performance after operating
		Selects from a limited range of possible prefixed actions		14	Identifies and selects appropriate set of actions
				13	Segregates or rejects according to measurement
				12	Changes speed, position, direction according to measurement signal
	Responds with signal			11	Records performance
				10	Signals pre-selected values of measurement (Includes error detection)
				9	Measures characteristic of work
From a control mechanism that directs a predetermined pattern of action	Fixed within the machine			8	Actuated by introduction of work piece or material
				7	Power Tool System, Remote Controlled
				6	Power Tool, Program Control (sequence of fixed functions)
				5	Power Tool, Fixed Cycle (single function)
From man	Variable			4	Power Tool, Hand Control
				3	Powered Hand Tool
			Manual	2	Hand Tool
				1	Hand

Each of the 17 mechanization levels in table 16 is classified depending on the power source (either the human or mechanical source), type of machine response, and initiating control source (the origin of control information). As can be seen in Table 16, Bright (1958) lists the different levels into three categories depending on who is initiating the control, the human (1-4), the human together with automation (5-8) or the automation (9-17). In each of those tasks, Bright lists what type of machine response that can be expected.

Similar to Bright, Marsh and Mannari (1981) define what they call "automaticity" in six levels from conducting the tasks manual, without any physical support, to full automated cognition with computer control (table 17).

Table 17 Levels of automaticity (Marsh and Mannari 1981)

Hand tools and manual machines	E.g. Pliers, hammer, files, etc.
Powered machines and tools	Muscles are replaced for the basic machine function, but machine action and control are completely dependent on the operator. Uses mechanical power, but man positions work and machine for desired action. E.g. electric tools
Single-cycle automatics and self-feeding machines	Completes an action when initiated by an operator. Operator must set up, load, initiate actions, adjust, and unload. E.g. Production machines without accessory automatic control system, grinder, planer, lathe, etc.
Automatic repeating cycle	At this level, all energy is mechanized. The automation carries out routine instructions without aid by the human. Starts cycle and repeat actions automatically – self-feeding. Loads, goes through sequence of operations, and unloads to next station or machine. No self-correction but obeys internal program such as cams, tapes, or cards. E.g. engine production lines, self-feed press lines, automatic copying lathe, etc.
Feedback by self-measuring and self-adjusting	Measures and compares results to desired state and adjusts to minimize error. Although feedback control of the actual surface of the Workpiece is preferable, positional control of the machine table or tools is of great value. E.g. feed-back from product, automatic sizing grinders, size-controlled honing machines, process controllers, etc.
Computer control and automatic cognition	Computer monitors multiply factors on which machine or process performance is predicated – evaluates and reconciles them to determine proper control action.

It can thereby be noted in both Bright's and in Marsh and Mannari's taxonomies that both taxonomies put focus on the support that the technological tools can give. However, both taxonomies combine the physical support with the cognitive in one single taxonomy.

4.2 Summary of the LoA concept

Williams (1999) stated:

> *"there must be a simple way of showing where and how the human fits in the enterprise and how the distribution of functions between humans and machines is accomplished".*

Based on the reviewed taxonomies and the division into mechanization and computerization, it can be presumed that there are a number of different taxonomies that could be fit into the model (in figure 2) by Williams. From a mechanized perspective, the level of automation or mechanization can be expressed in three levels, in line with Kern & Schumann (1985) and Duncheon (2002). The lowest LoA is manual, where the tasks are achieved without any support of the automation, tools or other form of technology. The intermediate LoA is semi-automated, and consists of collaboration between the human and the technological support to achieve the task. The highest level of physical automation is automated, which exclude the human from conducting the physical tasks. From the review of computerized taxonomies, it can be seen that there are in the mainly two ways of viewing levels of computerized automation. The first is similar to the physical support approach. Focus is on the interaction between the human and the technology, thereby identifying what the human and the technical system do under different LoA conditions and how they should co-operate. This approach, promoted e.g. by Sheridan (1980) has often be used as a starting point to optimize the task allocation of decision-making and information processing. The second way of viewing levels of computerized automation is to focus on how humans acquire information, process information and makes decisions according to psychological theory (Card et al. 1983). By combining those two views the level of computerized automation can differ, depending on what step of the information processing is supported. Parasuraman, et al. (2000) and Kaber, et al. (2000) presents a taxonomy based on the support the technical system could give the human at different stages by means of expert systems for more efficient information processing. As noted by Billings (1997), the level of computerized automation is a division of tasks between the human and the technical system. It is important to note in line with e.g. Sheridan (1980), that the role of the operator can vary depending on the level of computerized support. As seen in the review it can be an advantage to separate the physical and cognitive tasks when assessing the level of automation. Even so, in a manufacturing context consisting of a mix of both mechanized and computerized support there is a need of assessing both perspectives. Bright (1958) and March & Mannari (1981) did that by defining the level of automation depending on who was initiating the control task. By combining the two perspectives, the levels of physical support are connected to an equal level of cognitive support. There may be an advantage in assessing the level of automation using two connected reference scales, were the level of physical and cognitive support may vary depending on the need from the human.

5 Suggestion of a LoA definition and taxonomy to be used in manufacturing

Based on this review of different LoA taxonomies and in relation to the forthcoming empirical example (chapter 6) from industry, it can be argued that the basic definition of LoAs relates to the allocation of tasks of all types between the human and her technological support. On the other hand, automation within manufacturing is generally focused on mechanical components and physical task allocation strategies, such as the task of assembling the plinth or the roll front in the forthcoming empirical example. Even if many of those manufacturing processes seem only to involve automation of mechanical tasks, most of those tasks are controlled or supervised by computers for optimal performance over time, e.g. the hydraulic screwdrivers that are programmed to tighten the screw to a pre-defined torque. Therefore it is suggested in this paper, in line with Williams (1999), that it is important to recognize that automation in manufacturing, as well as in other domains, should be seen as an interaction between two types of tasks: physical tasks and cognitive tasks. The physical tasks are the basic core technologies, such as drilling, grinding, etc, and the cognitive tasks deal with the control and support of the physical tasks.

Based on the previous review, the level of automation within manufacturing can be defined as:

> *"The allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic"*

Focus in the definition should be focused on how the task can be achieved in the best possible way.

As seen earlier in table 2, most LoA taxonomies are either focused on the allocation of strictly cognitive tasks, e.g. Billings (1997), Endsley (1997) and Sheridan (1980) or on the manning level around the machines, e.g. Groover (2001).

By breaking down activities into physical and cognitive tasks, while still acknowledging the co-operation between human and technology, it can be useful to consider the task allocation as two independent reference scales relating to the two kinds of level of automation. Each of those tasks can then be ordered in seven steps, from totally manual control to fully automatic (table 18).

Table 18 LoA-scales for computerized and mechanized tasks within manufacturing

LoA	Mechanical and Equipment	Information and Control
1	**Totally manual** - *Totally manual work, no tools are used, only the users own muscle power. E.g. The users 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. E.g. The users 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 users' 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 consider being suitable. E.g. Thermostat*
7	**Totally automatic** - *Totally automatic work, the machine solve all deviations or problems that occur by it self. E.g. Autonomous systems*	**Totally automatic** - *All information and control is handled by the technology. The user is never involved. E.g. Autonomous systems*

The advantage, in relation to previous taxonomies, of using the two proposed reference scales in table 18 is that both the level of physical and cognitive support can be assessed in the same taxonomy. Since the two reference scales for assessment of physical and cognitive support are independent, the level of automation for physical and cognitive support can vary depending on the need from the human. Further, by using the taxonomy presented in table 18 as a base for a measurements methodology might it be possible to estimate the potential of technology and automation in different types of human-manufacturing system.

To explain the taxonomy (table 18) an empirical example representative for the manufacturing industry will be described in the next section.

6 An industrial example of a LoA assessment

The following description of a LoA assessment procedure (figure 5) is a generalized and simplified example based on our empirical experiences. It is presented to visualize the levels of automation during a defined part of office cabinet assembly in the Swedish furniture industry.

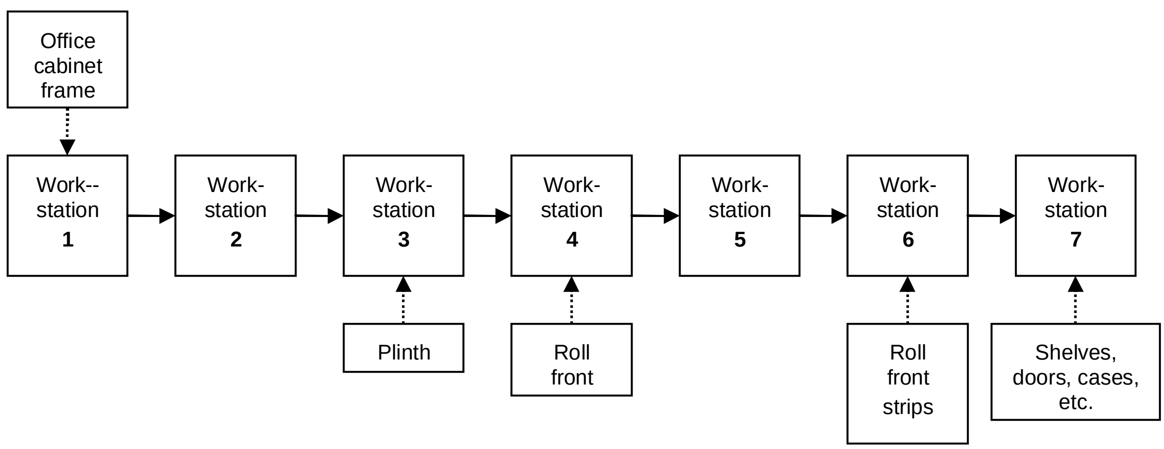

Fig. 5 An empirical example of office cabinet assembly

6.1 Context and list of operations in the example

When the cabinet enters the equipment-paced assembly line, the frame (consisting of the cabinet's sides, top, and bottom) has already been assembled. The cabinet is also positioned upside-down to simplify the task of assembling the plinth on to the bottom of the office cabinet.

- Workstation 1: Application of glue on the base of the office cabinet

Before the plinth can be assembled, the bottom side has to be prepared by applying glue on the bottom of the cabinet. The application of glue is done by an industrial robot, which means that the cabinet has to be positioned so that the robot can conduct the gluing operation.

- Workstation 2: Application of the plinth on base of the office cabinet

In the next step, the plinth is attached to the bottom of the cabinet by a robot in the plinth-assembly workstation, where the robot picks the right plinth from the plinth stock. Even if the assembly of the plinths works most of the time, the operator at the following workstation has to inspect the assembly. If the plinth has not been assembled correctly, the operator corrects the assembly by using a rubber hammer to force the plinth and bottom of the cabinet together. In some cases, the operator also has to correct and patch the gluing operation before the cabinet is sent to the next station.

- Workstation 3: Assembly of cabinet roll front

In the station where the application of glue and the assembly of the plinth are being checked, the roll front of the cabinet is assembled by hand. The operator picks the roll front with the right width from the roll front stock, and than inserts it into the roll front magazine on the topside of the cabinet.

- Workstation 4: Turning office cabinet from upside-down

The cabinet has to be turned for the remaining assembly. This is done by a robot, since the task is considered too heavy to be permanently allocated to humans. However, in case the robot is malfunctioning, the task is still performed by humans.

- Work station 5: Assembly of shelves

After the assembly of the roll front, the cabinet is turned and shelves are assembled into the cabinet. The shelves are picked from the shelf stock and assembled into the office cabinet with support of hydraulic screwdrivers.

- Workstation 6: Assembly of cabinet roll front strips

After the shelves have been assembled, the next step is to assemble the strips to guide the roll front. This is done by a robot that picks the strips from the strip magazine and nails it on to the cabinet.

- Workstation 7: Equipping the office cabinet

The final step of assembly is to equip the office cabinet according to the costumers' demands. The operators at the workstation get their instructions from the attached order form on how the cabinet will be equipped. Based on the order form, the operator equips the cabinet with shelves, doors, cases, etc. The assembly of the different equipments is done by hydraulic screwdrivers and, since the torque is of importance, the hydraulic screwdrivers have been programmed to tighten the screws to a pre-defined torque.

The manufacturing processes described represent the basis for a LoA assessment described in the next section.

6.2 Assessment of LoA

Based on the task descriptions in the empirical example in 6.1 and the LoA taxonomy in table 18, the LoA for Mechanical/Equipment and Information/Control can be estimated for each of each workstation. This is presented in table 19.

Table 19 Estimated LoA from the empirical example

Workstation	Task description	LoA – Mech. & Equip.	LoA – Info. & Contr.
1	Application of glue on base of the office cabinet	6	5
2	Application of plinth on base of the office cabinet	4	5
3	Assembly of cabinet roll front	1	2
4	Turning office cabinet from upside-down	5	5
5	Assembly of shelves	4	3
6	Assembly of cabinet roll front strips	6	5
7	Equipping the office cabinet	4	4

Further, by identifying the sub-tasks based on the main task for each of the seven workstations the allocation of tasks between human and automation can be visualized. E.g. workstation 2 that has the main task of assemble the plinth on to the cabinet has a number of physical and cognitive sub-tasks that has to be allocated between the human and the technology, as seen in table 20.

Table 20 The allocation of physical and cognitive tasks between human and automation in workstation 2

Workstation 2	Physical task	Cognitive task
Human	Correct and/or conduct the assembly if the plinth has not been assembled correctly	Supervise the industrial robot Inspect the assembly
Automation	Automatic positioning of the cabinet before conducting the automated task Pick the plinth from the plinth stock Automatic assembly of the plinth on the bottom of the cabinet	Decide which plinth that is going to be picked for assembly based on the control program Decide where to apply the plinth on cabinet based on the control program

The physical task for the automation is in the first step is to position the cabinet before the plinth can be assembled. According can to the reference scale in table 18 for the physical task can the LoA be assesses as $LoA_{M\&E}$ =5, since the workstation is designed for the specific task of positioning the cabinet. The same task can accord the cognitive reference scale in table 18 be assessed as $LoA_{I\&C}$ =6, since automation intervene and corrects the positioning of the cabinet if it is necessary. Next task for the automated workstation is to pick the plinth from the plinth stock. According can to the reference scale can the physical task be assessed as $LoA_{M\&E}$ =6, since this part of the automated system is design to both pick the shelf and assemble it on to the cabinet. However, the robotic assembly of the plinth is not always successful which means that humans, with or without support of a rubber hammer, sometimes do the assembly task. This means that the task is sometimes conducted at $LoA_{M\&E}$ =1 (by hand without the rubber hammer) and at $LoA_{M\&E}$ =2 (with support of the rubber hammer). By using the cognitive reference scale on the same example of picking the plinth from the stock and assembly, it can be determined that the cognitive LoA corresponds to $LoA_{I\&C}$=5, since the robot solution calls for the operators' attention in case of malfunctioning. On the other hand, if the task is conducted manually (with or without the rubber hammer), the cognitive LoA assessment would be $LoA_{I\&C}$ =1, since no support is given. The understanding for achieving the task is based on the operator's own experience and knowledge.

As noted by Price (1985), some tasks are neither possible to allocate to the humans, nor to the technological system. As seen in figure 1 by Price (1985), there is a maximum extent of the human capability to handle some tasks and in the same way has the technological system its limitations. LoA is also not static over time, but can be modified and adapt to the changing conditions for the manufacturing context. It would thereby be suitable to view the level of automation in terms of what are the limits of automation, or a relevant maximum and minimum for a particular machine or cell. Based on the empirical example in figure 5, the maximum and minimum LoA for each workstation can be estimated (table 21). Williams (1999) came to a similar conclusion, stating that there are identifiable sets of limits in manufacturing to what is humanly accomplishable. He also suggested that there are definable limits to automation in mission fulfillment tasks as well as in information and control tasks (figure 2).

Our empirical example in chapter 6.1, based on earlier case studies show that for the practical manufacturing situation a maximum or minimal level of automation in many cases may prove unrealistic in terms of investment cost etc. In the empirical case presented in chapter 6.1, an assessment of LoA based on e.g. interviews of the personnel will not reveal the "real" maximum of the LoA, instead a "relevant" LoA will result from the assessment. In our empirical example, the relevant LoA-levels are indicated (table 21).

Table 21 Relevant maximum and minimum of LoA for a particular machine or cell

	Mechanical and Equipment						
LoA	**Workstn. 1**	**Workstn. 2**	**Workstn. 3**	**Workstn. 4**	**Workstn. 5**	**Workstn. 6**	**Workstn. 7**
7							
6	Relevant max	Relevant max		Relevant max		Relevant max	
5				Relevant min			
4					Relevant max	Relevant min	Relevant max
3							
2	Relevant min		Relevant max		Relevant min		
1		Relevant min	Relevant min				Relevant min

	Information and Control						
LoA	**Workstn. 1**	**Workstn. 2**	**Workstn. 3**	**Workstn. 4**	**Workstn. 5**	**Workstn. 6**	**Workstn. 7**
7							
6							
5	Relevant max	Relevant max	Relevant max	Relevant max		Relevant max	Relevant max
4		Relevant min		Relevant min			
3					Relevant max	Relevant min	
2			Relevant min		Relevant min		
1	Relevant min						Relevant min

In the two reference scales presented by table 21, two assessed levels of automation are marked for each workstation:

The **relevant maximum** LoA describes a possible technical situation. It is considered when the investment cost not exceeds the value of the advantages achieved through automation. The consequences of a possible stop of manufacturing or breakdown also need to be taken into account. It is important not to automate more than what is necessary or justified, since investment costs rise rapidly. Another disadvantage of high LoA is that the system may become inflexible and rigid.

A **relevant minimum** of LoA can be favorable when work can be carried out at a suitable pace at an acceptable cost without jeopardizing work environment for people involved in the process.

The assessment of LoA makes it possible to choose a suitable LoA for each manufacturing process, and moreover, to identify a suitable span of LoA.

The existing and potential level of automation for each workstation is located somewhere in the range between maximum and minimum LoA, indicated by the grey area in Table 21. Thus, it is now possible to analyze the present situation and to judge possible future automation potentials.

7 DISCUSSION

We have presented a review of recent research on "level of automation" concept across several fields of research and industries. Our analysis suggests a possibility to apply two independent reference scales for assessment of automation, one for physical and one for cognitive tasks.

Further, as noted by Billings (1997), Endsley (1997), Endsley et al. (1997) and Satchell (1998), much of the previous research approaches in areas such as aviation and telerobotics have been primarily concerned with cognitive automation. The aim of the cognitive automation has often been aiming to speed up information flow and to provide decision support, thus supporting the operator in monitoring the situation. However, from a manufacturing perspective it is important to recognize in line with Williams (1999) that manufacturing processes in general consist of both physical tasks, e.g. replacement or support of human muscle power as well as cognitive tasks e.g. carrying out control and information tasks. Further, this approach is also in line with Bright (1958) and Marsh and Mannari (1981), who concluded that the manufacturing context consists of a mix of both mechanized (physical) and computerized (cognitive) tasks.

This indicates a potential in combining results from multiple fields of research to arrive at a relevant description of the actual automation situation in manufacturing contexts.

The review shows profound support for treating automation as a continuum of automation levels, from the lowest level of fully manual performance (based on the capabilities of the human), to the highest level of full automation (without any human involvement). Thereby it can be argued with support of earlier research by Endsley (1997), Inagaki (1993), Parasuraman et al. (2000) and Sheridan (1992), that automation is not all or nothing.

By breaking down the activities in line with Williams (1999) into physical and cognitive tasks, while still acknowledging the co-operation between the human and the technical system, it can be relevant to consider the allocation of tasks as two independent reference scales of LoA, relating to the cognitive and physical tasks. Each of those can then be ordered in seven steps, ranging from totally manual to fully automatic.

The advantage of using the two proposed reference scales, in relation to previous taxonomies of LoA by e.g. Billings (1997), Endsley (1997) and Sheridan (1992), is that both the level of physical and cognitive support can be assessed in the same taxonomy. Since the two reference scales for the assessment of physical and cognitive support are independent, the level of automation of physical and cognitive tasks can vary depending on the individual human needs.

However, as noted by Price (1985) and Williams (1999), some tasks are not possible to allocate to the human or to the technological system. As showed by Williams (1999), there is an maximum and minimum extent of the human as well as the technological capability to handle different tasks. Based on the model of limitations by Williams (1999) and the cases studies within this thesis, it can be noted that in term of e.g. investment cost, it is unrealistic for practical industrial situations to consider the entire span of each of the two reference scales. Therefore, and in line with Williams (1999) it is not relevant to discuss the assessment of LoA in terms of absolute maximum and minimum levels, but instead in terms of relevant levels of automation for each of the two reference scales.

8 CONCLUSION

The objective of this paper was to take a systematic approach towards changing levels of automation in semi-automated manufacturing systems. From a literature review performed across disciplines and industrial sectors it was concluded that levels of automation within manufacturing generally does not constitute a single step from manual to fully automated tasks. Instead, we have identified two independent "continuums", one for physical tasks and one for cognitive tasks. To enable assessment of the two levels of automation, two seven-step references scales where suggested and delimited by lower and upper boundaries. By assessing a) the relevant maximum, b) the relevant minimum, and c) the actual levels of automation for each work-task or workstation, the potential residing in increased or decreased automation can be identified. The resulting assessment can be used to increase total manufacturing system performance.

ACKNOWLEDGEMENTS

This paper contains results from the DYNAMO project. The authors are deeply grateful to the Swedish Fund for Strategic Research, specifically its ProViking programme, for funding the project. We would also like to thank colleagues and industries involved in the multiple parts of the DYNAMO project.

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