Model-based operator guidance in interactive, semi-automated production processes

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für Claudia und meine Familie

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Kurzfassung

Diese Arbeit befasst sich mit Fachkraftaufgaben in der Führung und Überwachung von technischen Prozessen. Die Übersicht der Publikationen der letzten Jahrzehnte eröffnet, dass insbesondere technische Prozesse mit enger Verknüpfung von Mensch und Herstellungsprozess bei den entwickelten Automatisierungsansätzen nicht hinreichend berücksichtigt werden. Die Integration von Prozesswissen und -erfahrung in das resultierende Automatisierungssystem bleibt eine offene Fragestellung. Neben der Einführung von Automation in Handarbeitsprozesse, die die Komplexität des Gesamtsystems erhöhen, ist die Gestaltung der Mensch-Maschine-Schnittstelle zum Automatisierungssystem von zentraler Bedeutung. Der Konflikt zwischen Handarbeit und Automatisierung wird in dieser Arbeit durch die Einführung einer Teilautomatisierung gelöst. Das Anwendungsbeispiel ist das Kaltharzverfahren, ein traditionell in Handarbeit bewältigter Herstellungsprozess für Gussformen. In diesem Prozess spielt die Fachkraft eine zentrale Rolle (z. B. durch ihr Prozesswissen und ihre Expertise), während die (intelligente) Automatisierung –geführt und überwacht durch die Fachkraft– anfallende physische Aktionen ausführt. Dies wird durch experimentell ermittelte qualitäts-beschreibende Prozessgrößen erreicht, die eine in-prozess Rückführung zum Bedienpersonal ermöglichen. Prozessführungsassistenz ist basierend auf die Formalisierung der Mensch-Automation-Interaktion gegeben. Durch die Bestimmung von situativen Informationen hoher Wichtigkeit aus dem resultierenden Mensch-Automation-System Modell bezogen auf das aktuelle Prozessziel, wird das bestehende Prozessmodell zur Überwachung und Prozessführungsassistenz des Gesamtprozesses genutzt. Die Gestaltung der Mensch-Maschine-Schnittstelle basiert auf einer detaillierten Analyse des Handarbeitsprozesses und ist als direkte, intuitiv bedienbare, markerbasierte Interaktionstechnik realisiert. Das integrierte Mensch-Automation-System sowie die zugehörige Mensch-Maschine-Schnittstelle inklusive Prozessführungsassistenzfunktionen wurden initial evaluiert. Die erzielten Ergebnisse werden hinsichtlich des individuellen, fachkraftabhängigen Prozesswissens und der Reproduzierbarkeit für den Ausblick diskutiert.

Abstract

This contribution focuses on the task of guiding and supervision of technical processes realized by human operators. The review of publications of the last decades discloses that especially technical processes with strong interconnection of human operator and manufacturing process are not adequately addressed by the evolved automation approaches. Integrating human process knowledge and experience into the resulting automation system is still a major concern. Besides the introduction of automation in a handcrafting process that is increasing the overall system complexity, the design of the human-machine interface to the automation system is of central importance. Within this thesis, the trade-off between manual manufacturing and automation is addressed by a semi-automation approach. The application example is the no-bake molding process, a mold manufacturing process for casts that is traditionally handmade. Within this process the human operator plays a central role (i.e. knowledge and expertise), whereas the (intelligent) automation is carrying out physical operation, which is guided and supervised by the human operator. This is achieved by experimentally identified quality representing process variables that allow for in-process feedback to the human operator. Process guiding assistance is given using a formalization approach of the human-automation-interaction. By deducing situative information of interest from the resulting human-automation-system model with respect to the current process goal, the established process model is used for supervision and assistance of the overall process. The design of the human-machine-interface is based on a detailed analysis of the handcrafted process and is realized as a direct, intuitively usable, marker-based interaction technique. The integrated human-automation-system and the corresponding human-machine-interface with process guidance assistance functionality is initially evaluated. The results are discussed for the future work with respect to the individual, human operator-specific process understanding and process reproducibility.

Contents

List of figures

List of tables

List of acronyms

ADE Algebraic differential equation (ADE)

AUTOS Artifact-User-Task-Organization-Situation (refer to Boy, 1998, 2011)

CBR Case-based reasoning (refer to Nwiabu et al., 2012a,b)

CBSA Case-based situation awareness (refer to Nwiabu et al., 2012a)

CTT ConcurTaskTree (refer to Paternò, 2000, 2003)

DoA Degree of automation (refer to Hancock et al., 2013; Manzey et al., 2012; Onnasch et al., 2013)

ELTS (Enriched) labeled transition system (refer to Combéfis and Pecheur, 2009)

EOFM Enhanced operator function model (refer to Bolton et al., 2011)

FIFO First-In-First-Out

FMC Flexible manufacturing cell

FSA Finite state automata (refer to Kim et al., 2010; Rothrock et al., 2011)

FSM Finite state machine (refer to Gill, 1962)

GOMS Goals, operators, methods, and selection rules (refer to John and Kieras, 1996)

GT Grounded Theory applied to recent automation interaction research (refer to Mattsson et al., 2012)

GTA Groupware task analysis (refer to Veer et al., 1996)

HAI Human-automation-interaction, -interface

HAS Human-automation-system

HCA Human-centered automation (refer to Billings, 1991)

HCD Human-centered design (refer to Boy, 2011)

HCI Human-centered-interaction/-interface

HMD Head-mounted display

HMI Human-machine-interface

HMS Human-machine-system

HTA Hierarchical task analysis (refer to Diaper and Stanton, 2003)

IfG Institut für Gießereitechnik gGmbH, Düsseldorf

IPS Information processing system (refer to Cacciabue, 1998)

LoA Level of automation (refer to Sheridan and Verplank, 1978)

LTS Labeled transition system

MABA-MABA Man are better at - Machines are better at (refer to Fitts et al., 1951, , in literature also known as Fitts' list)

MAD Methode analytique de description des taches (refer to Scapin and Pierret-Golbreich, 1990)

MPI Machine-process-interface

MPSG Message-based part state graph (refer to Altuntas et al., 2007; Smith et al., 2003)

NI National Instruments

ODE Ordinary differential equation

OFM Operator function modeling (refer to Cacciabue, 1998)

PCVS Process control and visualization system

PPE Personal protective equipment, e.g. gloves, hats, safety boots, dust mask

SA Situation awareness (refer to Endsley, 1987; Endsley and Kiris, 1995)

SOM Situation-operator-model (refer to Söffker, 2008)

TBM Task-based model (refer to Wang and Liu, 2008)

UAN User action notation (refer to Hartson and Gray, 1992)

UAV Unmanned, uninhabited, or un-piloted aerial vehicle (refer to e.g. Miller et al., 2011)

WYSIWYG What you see is what you get

Chapter 1

Introduction

1.1 Motivation

In Central Europe, and especially in Germany, demographic issues are arising that are causing changes to the way of manufacturing in order to keep global technology leadership. The manual molding process typically applied to mold fabrication of big cast parts is an example of strong interconnection of human skills and experience interconnected with the manufacturing process. The resulting products are globally appreciated for their quality.

The manual molding process for big cast parts is only a sample of an industry segment that is taken benefits out of human capabilities, however the forecast of labor population in Germany is distressing. According to Fuchs et al. (2011), labor population is decreasing in coming decades. In Fig. 1.1, the change of available labor population based on different model assumptions is illustrated. Independently of the applied assumptions whether (im)migration is considered or the reference population evolution of the year 2008 is kept, in the next decades the labor population is decreasing remarkably. With the underlying demographic issues, the amount of labor population is not only decreasing, but also aging is negatively contributing to the resource of handcrafting human.

Due to the reduced amount of labor population, the required amount of employees for comparable industry sectors such as manual molding is not and may not be available in future. However, skilled human worker are founding the key resource for handcrafting processes in casting industry and other domains. Common characteristic to handcrafted process is the reliance on experience and human skills paired with lack of process documentation.

Even though high process and product qualities can be achieved with the established handcrafted methods, the realized procedures are not taken any advantage of automation or automation support and thus, reproducibility is always an issue. In addition, the resulting quality is related to the individual worker leading to process steps with individual and not necessarily repetitive rebuilding procedures; an unknown contribution to process efficiency and cost effectiveness.

Typically, introducing automation requires detailed process understanding with fixed procedures and measurable/detectable process variables that can be mapped to sensors and actuators, a fact that represents the major hurdle of automation of handcrafting. The required process flexibility is the reason for the implemented manual working routines. Human-centered automation (HCA) is a main concern regarding reliability issues in automation of complex processes. However, even recent automation devices are not capable to automate processes with an advanced cross linkage of process technique and manufacturing skills as occurring in traditional handcrafting processes.

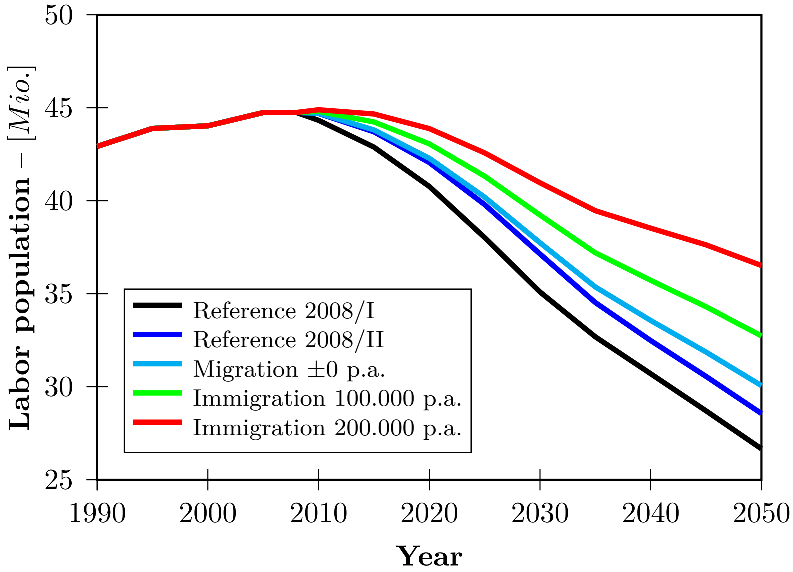


Figure 1.1 – Forecast of demographic influence on labor population in Germany (based on Fuchs et al., 2011)

Analyzing handcrafting applications for automation approaches regarding human factors on the one hand and economic goals on the other hand sometimes lead to a necessity of the human worker being integrated in the process. Thus, a role mapping becomes necessary, transferring the human worker from an ideal multi-variable sensory and actuatory process "element" into a process guiding and supervision role.

By introducing automation to manual processes according to HCA-approaches, the environment gains complexity. The confrontation of skilled human worker and automation needs corresponding preparation in terms of interface design and interaction logic. The integration of human workers into technical systems becomes necessary due to reasons of automation concepts that are not capable of completely integrating process knowledge and manufacturing skills for full automation of handcrafting processes. In such interactive, semi-automated systems human operators are facing a high amount of process information that need to be evaluated to conclude from skills and the knowledge-base of the individual human operator to necessary actions. In order to benefit from human abilities of information fusion and sophisticated comprehension of process coherence in complexity gaining environments, integrated approaches as framework for the development of assistance systems for guiding and supervision of semi-automated, technical systems are needed. Thereby, the advantage of having an uniform description of the entire, interactive system (consisting of human, machine, and technical process) as framework allows the implementation of methods for a situational, task-oriented assessment of existing information and corresponding filtering, respectively. The resulting reduced set of process-relevant information allows the human operator to stay focused during the decision making process and supports maintaining process reliability and quality.

1.2 Scope and organization

The thesis is dealing with the semi-automation of traditional handcrafting processes. Semi-automation is meant to integrate human skills and knowledge into a flexible Human-automation-system (HAS), in which physical actions are supported by automation and process guidance is realized by the human operator.

The underlying research is performed alongside with semi-automation of the no-bake molding process. Here, the additional focus lies in the spatial separation of human operator and molding process, as exposure of human worker to the noxious environment is to be avoided.

The scope of the thesis is to

- establish a methodical procedure to approach automation of handcrafting processes as flexible approach that is not application specific, instead the approach should be applicable to similar application domains,
- perform a system analysis of the handcrafting process using the sample application of no-bake molding,
- derive process guiding assistance based on the available process analysis,
- develop a prototype (demonstrator) to be used for the semi-automation of the sample process of no-bake molding,
- develop and designing of a Human-automation-interaction (HAI) and corresponding interaction technique that is capable to integrate human process knowledge into the process and allows for human operator assistance in process guiding and supervision, and
- perform an initial evaluation and provide proof of feasibility of the approach.

In Chapter 2 the fundamentals of HCA are introduced starting from a history overview of automation phases (Johannsen, 1993; Sheridan and Verplank, 1978) and the contributions to current state of the art. Actual focus on current automation development and its change with respect to traditional automation is pointed out. Typical questions of todays automation are raised in concern of human contribution to automation systems, hence integrated HAS are brought into the focus.

With the aim of establishing a framework to describe integrated HAS, in Chapter 3 formal models are reviewed and the Situation-operator-model (SOM) framework is introduced (Söffker, 2001). Using the SOM-based action space, model-based guidance and supervision concepts for integrated HAS are introduced that are reducing the amount of information within HAI. Visual technical process assistance is one essential contribution for the underlying interface that provides features of process control and guidance using direct manipulations methods.

The application and implementation of the concept to no-bake molding resulting in a semi-automated process is treated in Chapter 4. First, the process analysis of the traditional handcrafting process is performed using task analytic methods. A process quality representing variable is identified and characteristic diagrams for the use of a compaction tool are created. The field study is also used to validate reproducibility and reliability concerns of the semi-automated process. Second, with this knowledge, a Flexible manufacturing cell (FMC) is introduced spatially separating human operator and no-bake process to satisfy human factors as well as business concerns by proposing a marker-based interaction technique in co-relation to human operator assistance.

Both, the FMC itself and the corresponding HAI, are initially evaluated with skilled test persons from representative companies. The obtained results and the feedback are summarized in Chapter 5 showing the feasibility of the proposed manufacturing approach.

Finally, Chapter 6 summarizes the main achievements of the underlying research and the obtained benefits, the corresponding limitations, and the open questions for future work.

This thesis is based on pre-publications and conference presentations listed in the Bibliography on Page 128 as well as on supervised student theses listed on Page 129.

Chapter 2

Fundamentals of human-centered automation

Human centricity in engineering and especially in automation is a wide research with sophisticating challenges. The following sections give a big picture of the evolution of HCA in context of semi-automated Human-machine-system (HMS) without claiming to be complete.

2.1 Evolution of automation

Automation is present in every day life since decades with certain and individually understanding of what automation stands for. Referring to the Editors of The American Heritage Dictionaries (1994),

> **au·to·ma·tion** is
>
> 1. the automatic operation or control of equipment, a process, or a system,
> 2. the techniques and equipment used to achieve automatic operation or control, or
> 3. the condition of being automatically controlled or operated (from au·to·ma·tic).

The corresponding history of the word is also given (Editors of The American Heritage Dictionaries, 1994):

> "The words automatic pilot or automatic transmission bring to mind mechanical devices that operate with minimal human intervention. Yet the word automatic, which goes back to the Greek word automatos, 'acting of one's own will, self-acting, of itself,' made up of two parts, auto-, 'self,' and -matos, 'willing,' is first recorded in English in 1748 with reference to motions of the body, such as the peristaltic action of the intestines: 'The Motions are called automatic from their Resemblance to the Motions of Automata, or Machines, whose Principle of Motion is within themselves.' Although the writer had machines in mind, automatic could be used of living things, a use we still have, although not the primary one. The association of automatic chiefly with machinery may represent one instance of many in which we have come to see the world in mechanical terms."

In all the three stated definitions and the word's history cited above, a human operator is not necessarily present. However, even though a human operator is not explicitly mentioned, the irony of automation is the dependence on human operator at least for some minimal human intervention (refer to Bainbridge, 1983). This remaining portion of intervention as stated objective for human centricity and with no matter of which fraction, evolved over decades but is still a major discipline in research.

2.1.1 Review on automation eras

According to Sheridan (1986) and reviewed by Johannsen (1993) the historical development of HMS can be divided in three periods (referred to as eras) with different foci

- phase I (1940–1955): traditional human factors engineering (post-mechanization age),
- phase II (1955–1970): human controller (feedback age), and
- phase III (1970–1985): cognitive engineering (agent age).

During **phase I**, research work is performed relating physical measures and ergonomic features of human to their different perceptual channels, e.g. smell, hear, and taste. Furthermore, tasks and work station analysis with respect to human physical dimensions is popular leading to first attempts in (technical) Human-centered design (HCD).

As a result of traditional human factors engineering, several technical notes have been created that are enhanced to national and international regulations, such as e.g.

VDI/VDE 3699 (2005) *Prozessführung mit Bildschirmen*
(process control using display screens),

VDI/VDE 3850 (2000) *Nutzergerechte Gestaltung von Bediensystemen für Maschinen*
(user-friendly design of useware for machines),

BGI 523 (2007) *Mensch und Arbeitsplatz* (human and workplace),

DIN EN ISO 11064 (2014) *Ergonomische Gestaltung von Leitzentralen*
(ergonomic design of control centres), or

DIN EN ISO 9241-210 (2010) *Ergonomics of human-system interaction - Part 210: Human-centred design for interactive systems (ISO 9241-210:2010)*
(ergonomics of human system interaction)

to dictate or recommend technical design of machines, interfaces, or interactions.

In addition to extensions and refinements on human factors engineering, in the **phase II** the human operator's ability to close the (control) loop is investigated. Within this phase, available and extended control theoretic models are applied to the human operator that is seen similar to a technical element (machine). In control theory, this approach is often referred to as "human as controller" (e.g. refer to Jagacinski and Flach, 2003; Johannsen, 1977; Zühlke, 2012). The control theoretic description of the human operator in terms of transfer functions or block diagrams allows common control engineering-practices to be applied to both, human and machine part. These approaches are sufficient in describing the human operator continuously comparing the control variable with the own actions and

Table 2.1 – MABA-MABA list according to its original source in Fitts et al. (1951)

Humans appear to surpass present-day machines in respect to the following:	Present-day machines appear to surpass humans in respect to the following:
1. Ability to detect a small amount of visual or acoustic energy	1. Ability to respond quickly to control signals and to apply great force smoothly and precisely
2. Ability to perceive patterns of light or sound	2. Ability to perform repetitive, routine tasks
3. Ability to improvise and use flexible procedures	3. Ability to store information briefly and then to erase it completely
4. Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time	4. Ability to reason deductively, including computational ability
5. Ability to reason inductively	5. Ability to handle highly complex operations, i.e. to do many different things at once.
6. Ability to exercise judgment	

the resulting adaption to reach a certain target state. Thereby, an example from this phase (e.g. referring to Hesse, 1967) of the human's transfer behavior G_{H} can be given as

$$G_{\mathrm{H}}(s) = \underbrace{K_{\mathrm{p}}\frac{T_{\mathrm{l}}s+1}{T_{\mathrm{n}}s+1}}_{1.}\underbrace{\frac{1}{T_{\mathrm{i}}s+1}}_{2.}\underbrace{\exp^{-T_{\mathrm{d}}s}}_{3.}, \tag{2.1}$$

with the different factors being

1. an adaptable human behavior term with proportional factor K_{p}, first order delay with time constant T_{n}, and commissioning time constant T_{l},
2. a first order delay with time constant T_{n} for nervous and muscle system to react,
3. a reaction time constant T_{d} for perception and decision.

A similar description to the considered technical system the human is interacting with can be found based on the underlying physical relations describing the transfer behavior (e.g. refer to Lunze, 2010) or comparable modeling approaches. Thus, the combined model of human and machine allows a detailed analysis with respect to common control practices. With this early contribution on HMS in context of agricultural machinery, Hesse (1967) is aware of the adaptability of human operator in "human as controller"-systems. Thus, the first term of Eq. (2.1) only superficially represents learning and experience of the human, such that the parameters (K_{p}, T_{l}, and T_{n}) are changing over time that the human is interacting with the system to be controlled. Also, the factors are varying between different human individuals. During the time, the human is adapting to the system and is gaining experience. Especially, the latter fact of learning is a key characteristic of humans in HMS.

Overlapping the phases I and II, questions of task allocation between human and machines rise. So far, research is primarily focusing on how to automate technical processes, which is more related to available technology. In this context, Fitts et al. (1951) published the Man are better at - Machines are better at (MABA-MABA)-list illustrated in Tab. 2.1 leading to the answer of not only how but what to automate, which is considering constraints on the automation process. However, FITTS' list is discussed controversially by e. g. Inagaki (2003) or by Boy (2011), because of being "too rigid" to describe the interconnection of

HAI. In order to claim limitations of FITTS' list, Boy (2011) published a corresponding unFITTS' list.

FITTS' list is one popular example of inflexible task allocation that still survived the decades in scientific research. Winter and Dodou (2011) summarize the history of FITTS' list since its publication back in 1951. The results of this analysis and answers to questions, why inflexible task allocation is still popular in present research, is that during these decades and the improvements in computer science, FITTS' list reaches its limits and hence, needs to be extrapolated into today's technical abilities. Latter fact gives space for interpretation of the original intention of Fitts et al. (1951) leading to discussions among researchers (refer to Section 2.4.1).

In **phase III**, cognitive approaches are added to existing descriptions of HMS. On the one hand cognitive engineering includes the description of the human's behavior in decision making, action selection, and acting, and on the other hand to map human skills such as decision making or information fusion to machines. Several models, qualitative and quantitative, to represent human behavior interacting with technical systems are collected by Cacciabue (1998). The scope of the introduced models is to be able to found a description basis for simulation of interactive HMS. A simple approach is to create a separate model for each part of the entity, human, machine, and interaction. The requirements to the models are given by Cacciabue (1998) to be

- human model - cognitive functions, memory, resource allocation,
- machine model - physical variables, actuator, indicator, and
- interaction model - time management, logical interaction, dynamics,

for which itself representations are available. Present approaches of transferring human behavior models to machines, thus implementing machine learning and machine decision making evolved from such human models presented by Cacciabue (1998). The borders in HMS to separate human, machine, and interaction model become fluent. The internal relations are multi-modal and can be arbitrarily complex depending on the modeling requirements and the defined goal. Simple models of human operators and technical systems are already given in terms of (differential) equations (refer to Eq. 2.1) or as qualitative, descriptive models such as those introduced by Cacciabue (1998). Though, in the context of fully-automated systems terms such as supervisory control or tele-operation rise for understanding and discussion (refer to Sheridan, 1986).

Fully automation is one challenging aim of research in HAS. However, the pursuit of full automation finally ends not only in how to design and evolve technical solutions, but also questions of task or authority allocation are to be discussed. Issues of "over-automation" come up dealing with problems of interactive HAS (Norman, 1990). Thus, **phase IV** (since 1990) could be seen as phase of collaborative, flexible automation. This research is still under investigation and focuses on the flexible allocation of tasks and authority between agents that are machines or humans, respectively.

2.1.2 State-of-the-art of automation

During the evolution of automation, the aim of full automation is out of scope as fundamental research shows that human operators are necessary elements (refer to Bernotat, 2008; Parasuraman and Riley, 1997; Spath et al., 2009). Even though the technical abilities increased during the last decades, the proceeding process automation reaches a certain saturation that is directly related to efficiency, productivity, reproducibility, or similar economic benchmarks.

> "The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency.
> The second is that automation applied to an inefficient operation will magnify the inefficiency."
>
> – Bill Gates

As stated in the definition of automation, automation is usually seen as how to design control devices and displays in control rooms as well as the technical process behind, so that human operators feel comfortable in executing their duties efficient (which can be seen as place holder for any other benchmark). This view evolved from the history as automation challenges occurred in control rooms or cockpits.

Considering HCD approaches in automation disciplines aims gaining benefit from both domains, human and automation. Popular key issues that need to be addressed in interactive HMS are (adapted from Mattsson et al., 2012; Repperger and Phillips, 2009)

- trust and bias in automation
  (e.g. Dzindolet et al., 2003; Helldin and Falkman, 2012; Manzey et al., 2012; Muir, 1987; Tzafestas, 2009),
- cost of automation
  (e.g. Bustamante et al., 2009; Repperger and Phillips, 2009),
- (individualized) adaptive automation
  (e.g. Bustamante et al., 2009; Hancock et al., 2013; Inagaki, 2003; Kaber et al., 2005; Parasuraman et al., 2000; Scerbo, 2007),
- safety in automation
  (e.g. Boy, 1998; Spath et al., 2009),
- authority and responsibility in automation
  (e.g. Flemisch et al., 2012; Inagaki, 1993; Mattsson et al., 2012; Repperger and Phillips, 2009),
- performance of automation systems
  (e.g. Inagaki, 2003; Parasuraman et al., 2000; Repperger and Phillips, 2009),
- overriding automation
  (e.g. Repperger and Phillips, 2009), and
- social issues in automation
  (e.g. Repperger and Phillips, 2009; Tzafestas, 2009),

that need to be mentioned as present focus of HMS research.

Trust and bias in automation

Considering social approaches within automation science become important. Especially, trust and bias are of central interest as humans are interacting socially with technical systems (e.g. refer to Nass et al., 1995). Manzey et al. (2012) performed several laboratory experiments (process control tasks in a micro-world environment) on performance consequences of automated decision aids with changing Degree of automation (DoA) and the development of automation bias. As a result of the study, Manzey et al. (2012) point out that positive experiences with automation are weighing less than negative experiences, whereby the applied DoA is proportional to the gained performance in task accomplishment. A practical conclusion from the experiment is the benefit of an intermediate DoA with respect to costs and performance ratio.

According to Helldin and Falkman (2012) who reviewed work initiated by Muir (1987), trust in automation is one of three important issues (besides suitable task allocation and appropriate levels of automation) to be considered during the development of HCA systems. Helldin and Falkman (2012) emphasize the necessity of the three mentioned issues with respect to the fighter-aircraft domain, where balancing flight safety, combat survival, and mission accomplishment is of major interest and trust dependent. Domain-specific guidelines, such as limiting the amount of raw-data presented to the pilot, displaying the quality of information, reducing 'automation surprises', or making clear the purpose of automation are presented as summary of performed interviews and literature survey that are valuable for the design and implementation of automatic support systems in fighter-aircraft systems.

Tzafestas (2009) summarizes studies on trust in automation as a result of its importance in supervisory control functions (refer to Section 2.4.2). According to Muir (1987), trust in automation is subjective and operators are able to identify components to trust (error-free) and to mistrust (malfunctioning), which is further explored by e.g. Lee and Moray (1994). Riley (1994) confirms that trust is subjective and that the individual trust in automation depends also on self-confidence, workload, fatigue, and level of risk associated with the considered situation. Dzindolet et al. (2003) provide evidence through experiments that the transparency to the operator, why automation aids fails in some situations increases the reliance on automatic decision aids in error-free situations.

Cost of automation

Costs of automation are a main concern in industry and rarely scope of research but treated business cases. Erbe (2009) discusses cost-effective automation with respect to strategic low-cost automation. Affordable automation increases the competitiveness of small- and medium-sized businesses. Repperger and Phillips (2009) mention that cost-effective automation can also be seen as reducing functionality as humans are replaced by automation, such as in Un-piloted aerial vehicle (UAV). In this case, life-saving functionality (oxygen supply, ramps) or similar human-related design constraints (windows, cabin pressure control) are not necessary and thus can be omitted. However, including sophisticated control and/or automation devices to avoid human operator presence reduces benefits on costs.

Adaptive automation

Adaptive automation is synonymously used in literature for advanced task allocation between automation and human agents (refer to Section 2.4.1). This emerged from static task assignment (Fitts et al., 1951) to dynamic task assignment (Hancock et al., 2013). One aim of dynamic task allocation is to increase the overall system performance, which is constraining the assignment process (Kaber et al., 2005). Supervising the assignment process is another open challenge in adaptive automation, as the assignment also switches authority and reliability to the selected agent (Kaber et al., 2005; Scerbo, 2007). From a HCA view and to comply to laws or safety related regulations, primarily tasks are finally assigned by the human operator.

Parasuraman et al. (2000) and Parasuraman and Riley (1997) describe adaptive automation as a contextual change of the Level of automation (LoA) according to 'situational demands'. Situational demands are seen as triggers to pre-defined routines that are retrieved if related requirements are fulfilled. Defining requirements implies a detailed understanding of the situational demands and corresponding actions, which is the central concern in safety of automated systems.

Safety in automation

Safety in automation has several sub-branches, such as process/operational safety, environmental safety, or human safety with examples from chemical or process industry, surgery, or cockpit domains. An additional field of safety in automation is automation of safety-critical functions, such as auto-landing, emergency-shutdown of plants, or auto-inflating of life vests. Safety is always a question when there is the need to deal with unexpected situations and to follow specific procedures. According to Boy (1998), typically the human operator is not a good procedure follower. Human operators tend to recall procedures imperfectly in time-critical situations; something that is simple to implement in automation.

Repperger and Phillips (2009) state that through tele-operation the level of safety of human operator is substantially increased in interactions in hazardous environments. However, introducing automation does not necessarily increases safety in interactive human-robot/automation systems as there is still a remaining risk of e.g. collision (Oberer-Treitz et al., 2010).

Spath et al. (2009) focus on operational safety. Increasing operational safety means development in the systems reliability, following design strategies for safety issues (which is also part of useware engineering - refer to Zühlke, 2012), and minimizing risks of mechanical hazards to provide highest protection possible to the operator of the system. Safety in automation is also an issue in adaptable automation and how responsibility and authority should be shared in emergency situations.

Authority and responsibility

The relation of DoA and responsibility allocation with respect to a current situation of the system is probabilistically investigated by Inagaki (1993). During this time, the human operator is seen as 'locus of control' and the allocation of the full responsibility to automation is criticized as the human operator approves the authority of the automation in advance to an emergency situation (refer to Flemisch et al., 2012; Johannsen, 1993).

Trading authority and responsibility between human operator and automation is the consequence of automation in general. Increasing the DoA or LoA is directly affecting the transfer of potions of authority and responsibility to the automation (Repperger and Phillips, 2009). Keeping the human operator in the loop even in cases, where automation takes over authority and responsibility of reactions to events, is a known issue in systems with a high DoA, LoA (refer to Billings, 1991; Norman, 1990).

Flemisch et al. (2008, 2012) disclose a balancing approach to visualize shared authority and responsibility in an adaptable HAS within the driver-car domain. The relation of authority and responsibility in HMS is discussed on an ontology base and extended by ability and control. Thereby, ability stands for “the possession of the means or skill to perceive and/or select an adequate action and/or act appropriately”. Authority “of an actor can be defined by what the actor is allowed to do or not to do. Usually, authority is given to an actor beforehand by the system designer and has an impact on evaluations after the use, e.g. in the case of an abuse of authority.” Responsibility “is assigned beforehand to motivate certain actions and evaluated afterwards, where the actor is held accountable or to blame for a state or action of the human machine system and consequences resulting thereof.” Control “means to influence the situation so that it [the situation] develops or keeps in a way preferred by the controlling entity.” An illustration of the relation of the balance contributors from a human-centered view is shown in Fig. 2.1. Concluding from Flemisch et al. (2012), based on a LoA-view human and automation can also share authority and responsibility, however from a HCA view the final choice and global authority should be left to the human operator.

Overriding automation

Overriding automation by the human operator or overriding human operator interventions by automation is also an issue of dynamic task allocation with social constraints (refer to Inagaki, 2003). In cases of risk and danger to human enforce automated routines (also redundantly) to be considered to satisfy safety regulations meaning to allocate full authority (in this case also full control) to automation (refer to Kaber and Endsley, 2004). Repperger and Phillips (2009) confirm the validity of patronizing human operators in safety-critical situations and recommend to include rules to decide whether automation or human operator to intervene.

Especially, safety-critical situations are studied in detail in literature. Summarizing a subset of literature (Bengler et al., 2012; Inagaki, 2003; Kaber et al., 2006, 2009; Parasuraman and Riley, 1997; Poncela et al., 2009; Pritchett et al., 2014; Repperger and Phillips, 2009; Skjerve and Skraaning Jr., 2004; Spath et al., 2009) authority in safety-critical situations (defined depending on the research field, e.g. human-robot cooperation, driver-vehicle interaction, cockpit automation) is fully given to automation, whereas full authority in situations where any doubts on sensory data exists is given to human operator.

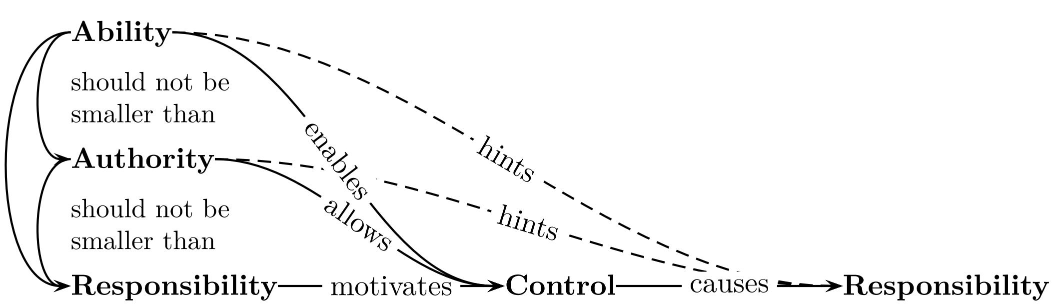


Figure 2.1 – Relations between ability, authority, control, and responsibility according to Flemisch et al. (2012)

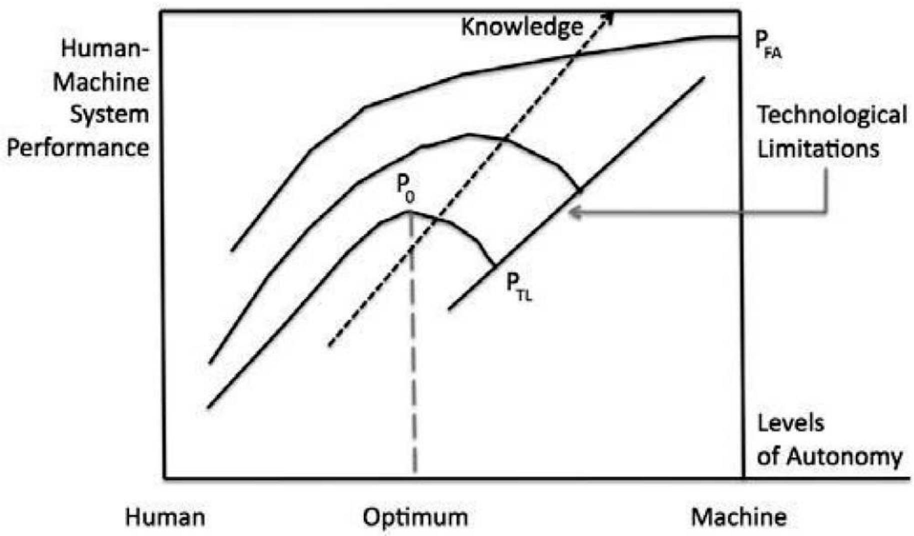


Figure 2.2 – HMS performance versus levels of autonomy according to Boy (1986)

Social automation and performance of automation systems

Social effects of automation can be seen from different perspectives. From the human worker view, automation has consequences on the individual work, working routines, and skills; in literature referred to as "alienation of human operator" (Repperger and Phillips, 2009). Meaning a change of the workplace and corresponding tasks. Cooperating with automation implies socially accepting automation, which is treated in detail in human-robot interaction research. Metaphorical, automation should be seen as teammate and not as antagonist. This view of automation can be supported by adequate design of automation leading to a social acceptable design of automation that additionally takes into consideration constraints such as economical design (Cernetic, 2003; Schaefer et al., 2012).

The company has its focus on process reliability and safety, reducing manufacturing costs (labor), or increasing product quality by using automation. Repperger and Phillips (2009) describe social issues caused by automation, by decreasing self-confidence and loss of identity of human. This is confirmed earlier by Hoc (2000). Social automation can also consider aspects of task allocation (pilot cockpit or driver-car domain) and the question of what (kind of) tasks are left to the human operator supporting self-confidence and reducing loss of identity (Hancock et al., 2013). Social automation is also related to trust and bias, and thus related to performance of the intended socio-technical systems.

Boy (1986) gives an example of the performance of a HAS in the chemical process domain that depends on the LoA and the autonomy of human and machine (refer to Fig. 2.2). Fig. 2.2 illustrates that there is an optimal LoA with respect to the HMS performance depending on the knowledge of the HAS. If the knowledge of the HAS is completely available and understood, the optimal performance can be achieved with full automation. However, usual there are assumptions and prerequisites defined to a considered HAS leading still to an optimum of LoA, but also to a remaining uncertainty of HAS behavior making human intervention essential for the HAS working within desired parameters.

The aforementioned paragraphs confirm the various research field of HAI. The scopes vary from technical implementation design, general task allocation, process guiding authority, reliability, responsibility, and safety. Due to complex interconnection of technical, social, and business questions, the design and analysis is sophisticated and allows space for discussion. Approaches in optimizing HAI vary as the domain is changed to consider domain specific constraints. From this perspective, unified approaches to describe, analyze, design, and implement HAI become reasonable. Therefore, a general understanding of the entity of HMS is essential.

2.2 Human-machine-systems (HMS)

From an engineering point of view, designing an ideal HMS can be seen as multi-objective function optimization problem with a non-unique solution. By advancing technology, the initial condition or constraints are not only varied according to the domain but also by availability of technology. Thus, a HMS design (solution) as of today might be worse compared to a HMS design in future. Regarding solution candidates for today or for future approaches, the understanding of human and machine abilities is necessary, in order to formulate the multi-objective function correctly. However, extrapolation into the future is challenging, thus the final HMS design is always a compromise of requirements and available technology.

2.2.1 Components of human-machine systems (HMS)

In Fig. 2.3, the topology of a general HMS is illustrated. This minimal HMS illustration consists of

- human operator (user),
- machine / automation, and
- Human-machine-interface (HMI), (HAI respectively).

The human operator is a generalized representation of a human being with respect to skills, ethnicity, ergonomic measures, or gender. Further specializing may consider specific ranges to narrow requirements to a defined analysis. The machine part of HMS is representing any technical system rather than being restricted to represent only specific machines. The connecting interface is an essential component and treated multidisciplinary.

Human operator (user)

The human model evolved through the eras and takes into consideration cognitive abilities. Cacciabue (1998) structured a human model as illustrated in Fig. 2.4. Key characteristics of human operator included in the model are

- perception,
- interpretation,
- planning (behavior-related), and
- execution

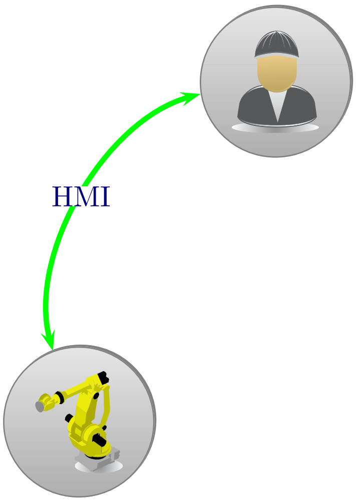


Figure 2.3 – Illustration of a HMS

that are widely treated as the human cognitive functions in literature referred to as reference model of cognition which is based on the Information processing system (IPS). Cacciabue (1998) added processes of memory/knowledge base and allocation of resources to the human model for simulation purposes and prepares the human model to interact with the machine model.

The necessity of human operator within automation system (even in highly automated systems) for at least a minimal potion of manual intervention is a famous irony of emerging automation (Bainbridge, 1983). Even though the designer view on the human operator is affected by unreliability and inefficiency. Describing and forecasting of human operator's individual behavior is sophisticating and is seen as critical component in control systems (HAS) (Rubin et al., 1988). Even the argumentation of an observed behavior opens space for discussion and interpretation as human behavior 'is recognized as [...] difficult' (Cacciabue, 1998).

As introduced in Section 2.1.1, depending on the technical system to be analyzed, the human operator is also treated as an element of the technical system. This "technization" or "mechanization" of human operator allows dynamic analysis of a joint HMS. However, ambitious features of the human operator's nature are completely neglected and only its "transfer behavior" in terms of how much time is needed until reacting with which dynamics is considered. According to Bainbridge (1983), a human operator is characterized with respect to its

- manual control skills (similar to physical ability),
- cognitive skills (similar to mental ability),
- monitoring, and
- operator attitudes (similar to behavior).

The human model evolved through the eras and is often not treated separately according to behavior (human-oriented) or role (automation-oriented) descriptions. For both, behavior

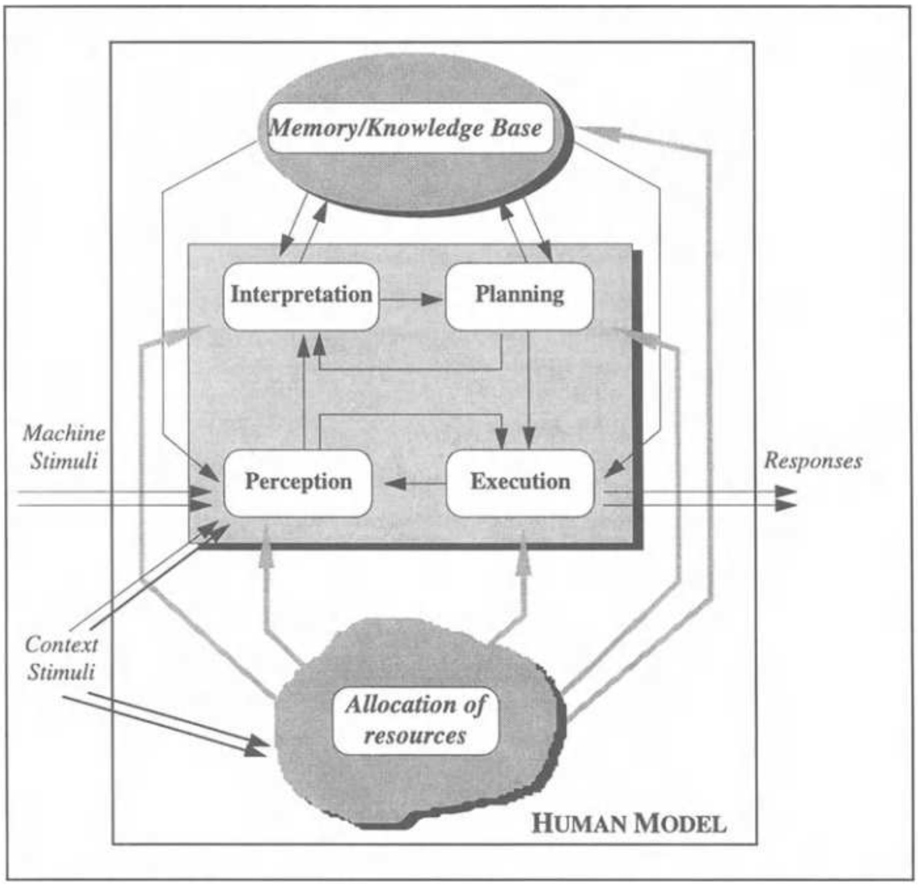


Figure 2.4 – Structure of human model according to Cacciabue (1998)

and role, figurative descriptions such as metaphors are popular in literature. Additionally, there are also terms like tasks and skills to consider.

Human behavior in the early stage of automation is seen as transfer element or later it becomes more general as input/output-system. Thereby, a transfer element in the classical way is representing almost static behavior according to the transfer function, whereas an input/output system can also account for flexible output generation such as Enhanced operator function model (EOFM) of Bass et al. (2011) depending on further inputs such as tasks or goals. However, the behavior of human operator is rather adaptable, flexible and not based on rules or algorithms than static and might not be repetitive. Thus, a human operator is not a good procedure follower (Boy, 1998), which is as important as being creative in unusual situations. When considering the human operator's behavior more flexible, the description of this autonomous agent might be unmanageable and less predictable (Rothrock et al., 2011) leading again to an input/output technique, which in this case is affordance based (Kim et al., 2010). Another way to view the human operator is to use the analogies of a resource. A resource means that input is a question of availability of a resource, and if the availability is given, then the human operator is providing the according action. There are a variety of examples, where especially the major characteristics of a human operator such as creativity or adaptability are necessary to handle unusual situations (Bainbridge, 1983).

Boy (1998) separates to basic behavior requirements of human operator in control of complex dynamics systems, goal-driven and event-driven. The difference can be figurative

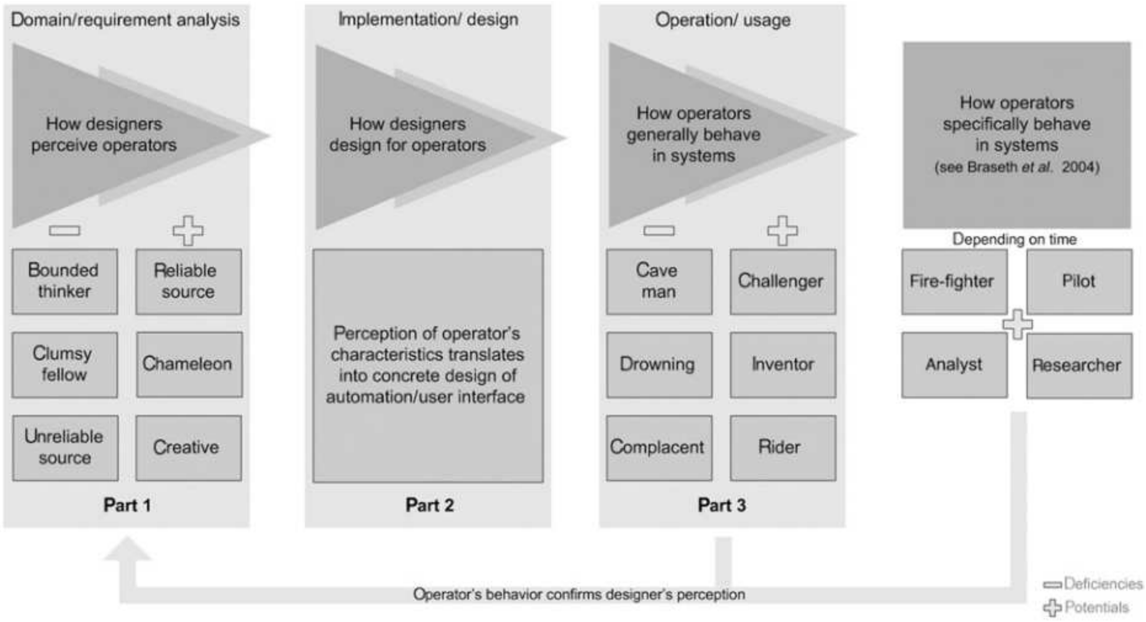


Figure 2.5 – Framework of analogies describing the human operator according to Nachtwei (2011)

expressed by a fire-fighter behaving event-driven, whereas a politician rather behaves goal-driven. In Fig. 2.5, an overview of analogies of human behavior in recent literature is given (refer to Nachtwei, 2011). From this perspective, the behavior of human operator is assigned to different analogies, e.g. reliable source as for process specialists, however process designer's analogies assignment may not coincide with interface designer's assignment or even with the real behavior of the operator. This is a major cause of mis-leaded design of interfaces.

The behavior of the human operator is connected to its role in automation. Dekker and Woods (2002) state that introducing automation creates new or additional human roles, which is equivalent to that new technology changes tools of people, who are forced to adapt. The **human role** changed and emerged during the automation eras from being actor (Cacciabue, 1998; Pawlowski and Mitchell, 1991) to become a/the

- risk manager (Hoc, 2000),
- locus of control (Billings, 1991, 1997; Inagaki, 1993),
- supervisor (Altuntas et al., 2007; Bodner et al., 1995; Cacciabue, 1998; Mitchell and Saisi, 1987; Nemeth, 2004),
  - monitor,
  - decision-maker,
  - information processor,
  - closed-loop controller,
  - information encoder and storer,
  - discriminator and pattern recognizer,
  - ingenious problem solver, or

- process provider (Altuntas et al., 2007).

The variety of roles that can be assigned to the human operator includes different levels of authority and responsibility and can also be changed during the process depending on the situation (refer to Flemisch et al., 2012). The benefit of assigning roles with their peripheral characteristics such as tasks and skills lies in their definition; as roles are less complex to define as personnel individuals (Hollnagel, 2003). Important is that with succeeding and availability of technology, the HAS are gaining complexity, however the human role is not part of the HAS design (Thurman et al., 1998). As opposed to technical system components, the role of human operator is given per default and a product of the final system design.

Accomplishing **tasks** require specific **skills** and corresponding roles to be assigned to the operator. If an adequate skill and the corresponding role is not available to a specific operator, the task cannot be accomplished without any external support (e.g. automation agent, or another human operator). Bengler et al. (2012) state that dynamically changing roles can be used to realize different levels of cooperation or collaboration as roles typically are related to tasks.

Automation (machine)[1]

Designing machines or automation is historically connected to available technology. Parasuraman et al. (2000) and Parasuraman and Riley (1997)

> "define automation as a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator."

Thereby, the human model as illustrated in Fig. 2.4 serves as structural blueprint for developed automation solutions. Goodrich and Boer (2003) refer to "the human operator as a template for automation." Thus, similar as to the human component in HAS, the automation component can be reviewed considering its

- behavior,
- role,
- task, and
- skill

related to an underlying process to automate.

Automation behavior is traditionally opposing the human operator and neither creative nor unpredictable. Automation behavior follows certain rules or algorithmic descriptions as illustrated in Fig. 2.6. In this model, Shin et al. (2006) is modeling automation as state transition system (based on Message-based part state graph (MPSG), more details in Section 3) similar to a classical input/output-system. According to Cacciabue (1998), plants (=automation or machine) and working environments are usually represented by their physical process descriptions, e.g. balance equations, conservation principles and logical correlations (models). Furthermore, Cacciabue (1998) states that the automation model is necessary to be as detailed as the human model. Consequently, the blueprint approach

[1] In the following, machine and automation are treated in the same way, thus the term automation will be equivalently used as for machine.

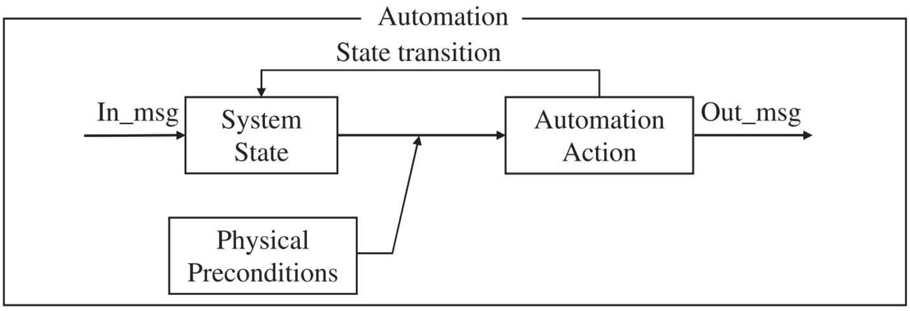


Figure 2.6 – Automation model according to Shin et al. (2006)

is becoming popular to converge to an unified description of human and automation including cognitive functions to automation. Recent research and development is extending the traditional view on automation behavior to include cognitive abilities such as those illustrated in Fig. 2.4. Degani et al. (1999) contribute adaptable automation behavior by analyzing modes in automation. Mode (behavior) means that automation can behave differently to a given input depending on the mode being active. The mode change can be triggered internally (automation-ended) or enforced externally (operator-ended). This way of dealing with automation modes is strongly related to automation surprises. Automation surprise represents automation behavior which is not expected by the operator (and may be not intended by the designer) and that the human operator is not aware of (refer to Sarter and Woods, 1997). In literature, this is often referred to as mode awareness[2] of the operator in the cockpit domain, but this is also a case for control rooms (e.g. Adachi et al., 2006; Flemisch et al., 2012; Kaber and Endsley, 2004; Onnasch et al., 2013; Stanton, 2005; Tzafestas, 2009).

With emerging automation, both human and automation roles change. The **automation role** can be seen as substituting the roles released by the human operator. This means applying automation not only means to apply roles to human, also automation receives roles as **tasks** are connected with it and vice versa. A common role assigned to automation is the actor or the slave, which might be assigned even before improving the automation, but they might be extended. Due to the fact, that enhancing technology means developing advanced automation (extending **skills**) that makes sophisticated solutions available, the human activity is mapped to automation performing the actions.

2.2.2 Interfaces and interaction

In HAS, interfaces offer possibility for interactions. Both, the interface(s) (HMI, Machine-process-interface (MPI)) and the interaction(s) (interaction technique), are subject to design questions and constraints restricting the amount and the way of data exchange between human and automation. Design and constraints have sources e.g. specified to the

- user group,
- environment,
- application, or

[2] Awareness, such as mode awareness or situation awareness (Endsley, 1987) are psychological terms viewed from an engineering perspective and detailed in Section 2.4.2

- comparable characteristics.

Degani and Heymann (2002) summarize HAI as consisting of four elements

- the machine's behavior (see above),
- the operational goals, or task specification (e.g. tasks),
- the model that the user has about the machine's behavior (called the user model or mental model), and
- the user interface (through which user obtains information about the machine's state and responses).

Interface and interaction principle are close related to account for each other. In some cases interface or interaction design is treated separately and leads to adaptation issues of operator. User-centered design approaches are dealing with this interconnection and are further discussed in Section 2.3. In general, the relation of interface and interaction design can be expressed by

> "achieving an optimal, mutual interaction between human and automation by an adequate design"

elevating the interface and interaction to the central design element in HAS.

> "Conversely, the more obscure the interface is, the more procedures are needed to insure a reasonable level of performance."
>
> – Boy, 1998.

Achieving adequateness of both designs can be realized e.g. by following HCA approaches. On the one hand the interface allows the human operator to input information. Provided information is evolved through the interface to the automation, where actions are triggered. On the other hand, feedback of the automation is provided to the interface and thus closes the loop. Weaknesses of the interface in illustrating feedback information have a direct connection to weaknesses in interactions (Trouvain and Schlick, 2008).

Weyers et al. (2012) separate the interface into two parts, interaction logic (similar to behavior) and its physical representation (indicators, screen, haptics). This separation is promising in order to deal with adaptable interface design, which can be seen as advancement to the approach of Weyers et al. (2012). In this sense, adaptable means situation-dependent rearrangement of the interface design. However, it could also be understood as situation-dependent behavior adaption. Both, design and behavior adaptation can be viewed as 'interaction modes' of the interface allowing different levels of information exchange. In this context, if different modes are available, questions of mode awareness rise. Mode awareness manifests, if the relation of presented information and the underlying machine behavior does not coincide with operator expectations (Adachi et al., 2006). In complex interaction domains (e.g. cockpit), still the operator (e.g. pilot) is the locus of control, independently of the active mode (Billings, 1991, 1997). Referring to Inagaki (2003), operator expectations can include information about the actual action performed by the automation, the "planned" action in future, and the reasoning why this action is performed (especially in adaptive automation systems).

Interaction principles (modes as of the original source) are discussed by Chao (2009) and differ into

- data interaction, such as graphs, tables, bar codes,

- image interaction, such as visual processing, perceiving, and recognizing pictural information,
- voice interaction, such as sending and capturing of spoken commands, or
- intelligent interaction, such as learning from the operator (next generation interfaces).

This variety of possible interaction principles offers a wide range for designers. Since designer and operator are often building bridges to explain or to understand each other, metaphoric description are widely used. Analogously to metaphoric descriptions of the behavior of operators and automation, in literature similar descriptions for interaction and corresponding interface design is applied. The interface is seen as

- communication host, managing the human and automation dialog (Sattar and Dudek, 2011; Schenk and Rigoll, 2010; Shin et al., 2006),
- master-slave manager, forwarding orders to (tele-operated) devices and delivering feedback (Feth et al., 2010; Sheridan and Verplank, 1978; Spath et al., 2009),
- filter, mapping user behavior to machine behavior and vice versa (Degani, 2012; Trouvain and Schlick, 2008),
- window, allowing a focused view into a complex automation environment or machine behavior abstraction to fit the interface (Heymann and Degani, 2007), or
- natural interface, translating human body movements into inputs (Sato et al., 2007)

and the interaction analogies as

- rider-horse metaphor for highly automated environments (Flemisch et al., 2008, 2012),
- button-pusher in control rooms (Bainbridge, 1983; Hancock et al., 2013; Sheridan and Parasuraman, 2005)
- natural interaction (pointing, verbal, force feedback, or similar) (Cerlinca and Vlad, 2012; Inaba et al., 1999; Sato et al., 2007)

to name a few.

According to Krüger et al. (2009), interfaces for hybrid assembly systems (as representatives to semi-automated HAS) can be divided into two classes,

- remote interfaces such as visual interfaces, interfaces for gestures and voice and
- physical interfaces such as haptic interfaces, displays and Head-mounted display (HMD) as well as force feedback systems.

The two classes introduced above can be mapped to certain role distribution, e.g. remote interfaces are typically for communication hosts or window interfaces, whereas physical interfaces can be viewed as master-slave manager or filter.

In the domain of process control, dialog interactions are common practice. Schenk and Rigoll (2010) summarize different dialog techniques with respect to their level of intuition (refer to Fig. 2.7).

Certainly, with increasing intuition, the implementation of the interaction principles is gaining complexity. New trends in advancing interaction techniques and interface designs

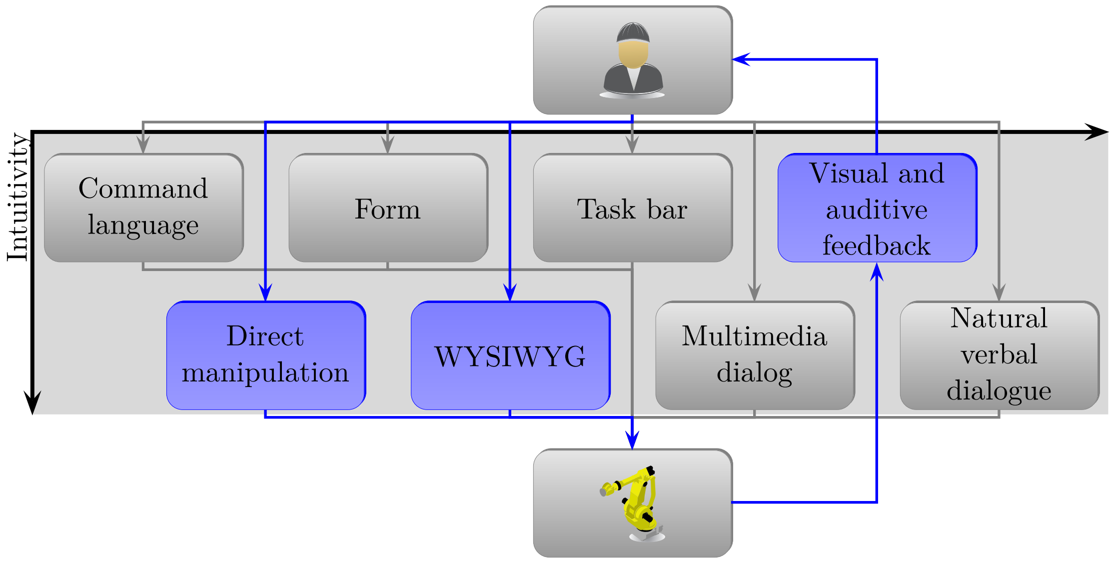


Figure 2.7 – Overview of human-machine dialog techniques according to Schenk and Rigoll (2010)

are popular in off-work environments (e.g. cell phones, smart TV, video games console). This accelerates interaction learning of operators, however leads also to an expectation level of how interaction should work in a specific way, which might not be satisfied in all interaction techniques applied in process control domain.

Summarizing the state of the art, the triangle of HAS as illustrated in Fig. 2.8 is subject to individual behavior, assumed role, assigned tasks, and available skills of interactive components that additionally are underlying the environment or other (physical) constraints. The human operator and automation are strongly related to each other and additionally to the interface design and the applied interaction principle. This fact makes evolution of an interlocking design approach necessary, since the entity of the HAS is connected to the system's performance.

2.3 Human-centered design (HCD) of automation

The combination of human individuals and machines to an entity is part of human engineering science. As of 1962, human engineering is pursuing the goal of optimizing the design and the co-action of human individuals and machine(s) with respect to benchmark constraints. Thereby, adapting the machine to the human is the common objective (refer to Bernotat, 2008). However, the availability of technical solutions is limited, thus there is always the need of human intervention in combination with human adaption to the machine or machine components. Designing automation in a human-centered manner or human-centered automation (HCA) can be seen as intersection of ergonomics, human factors, and engineering. Depending on the application (e.g. medicine, aeronautic), specialists in the discipline of contemplation are also considered. In literature there are two terms commonly used, HCA and HCD to describe human centricity in combination with technical systems. Billings (1991) introduced the term HCA in the domain of aviation, when HCD is already popular and represents the human side of automation (refer to Cowan, 1957). The difference of HCA and HCD is the stage of occurrence. HCD is applied when there is a (complete)

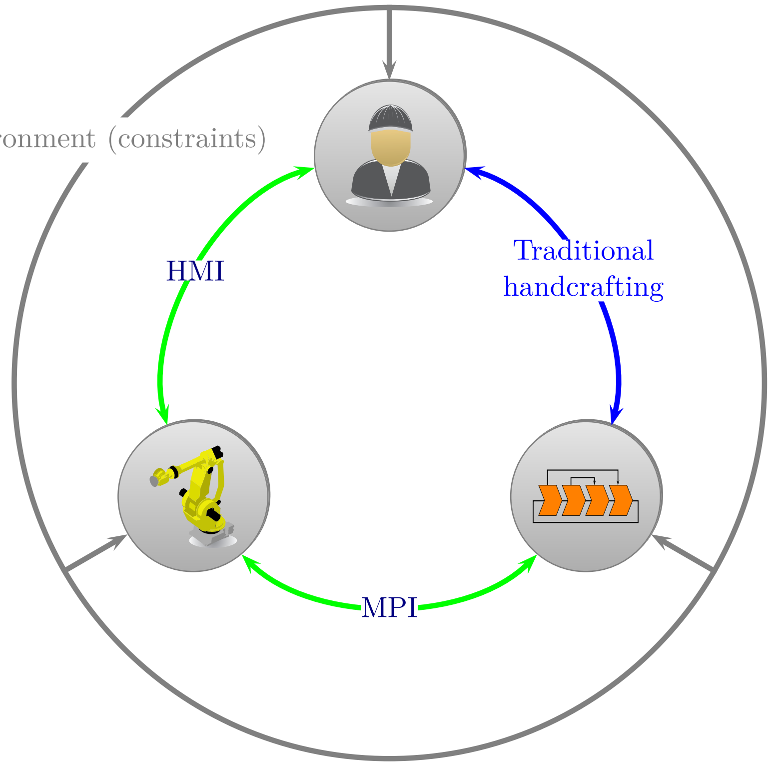


Figure 2.8 – Triangle of HAI (Langer and Söffker, 2014)

new design for an HMS starting almost from sketch, whereas HCA is added to an existing system or process (refer to Boy, 2011). The multidisciplinarity of HCA is illustrated in Fig. 2.9.

Goodrich and Boer (2003) state that

> "human-centered automation is a magnificent ideal, but one that is difficult to achieve in practice."

Boy (2011) adds that

> "usually, human-centered design is scenario-based and prototype-based, [...]"

where the deep relation of components is responsible for. This makes systematic approaches reasonable but also complex. Incorporating cognitive science to human-centered approaches offers a variety of popular terms in literature without any delimiters making understanding and discussion complex, since the common sense is missing. The rose family is a particularly matching metaphoric description of this term variety (refer to Hoffman et al., 2002). In the following, HCA is meant to be a part of HCD as also design approaches are used to gain performance at several layers in HCA.

2.3.1 Principles of human-centered design (HCD)

Human centricity approaches are mainly concentrating on the interface and the interaction principle design, and secondary on the technical solution of automation. Mattsson et al. (2012) performed a literature review based on Grounded Theory (GT) methodology on a

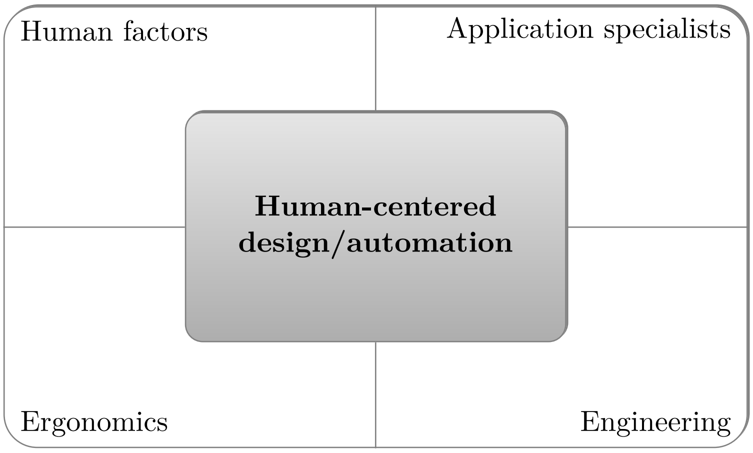


Figure 2.9 – Multidisciplinarity of HCA

literature basis from 2000 to 2011 that can be applied to production environments and categorized the recent development in HAI into three groups

- human-centered (e.g. trust/reliability, awareness),
- automation-centered (e.g. LoA, task allocation), and
- interaction-centered (e.g. usability, adaption).

Confirming the variety of terms in the field of human centricity and due to the interface and interaction being in the focus, HCD is often referred to as Human-centered-interaction (HCI). However, solving human-related questions related to the human or automation component are equally addressed by HCI principles. The SIGCHI, the association for computing machinery special interest group on computer-human interaction, describes HCI as "a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them (Hewett, 1992)".

According to Stone et al. (2005), HCD (here referred to as user-centered design)

> "is an approach to user interface design and development that involves users throughout the design and development process. User-centered design not only focuses on understanding the users of a computer system under development but also requires an understanding of the tasks that users will perform with the system and of the environment (organizational, social, and physical) in which they will use the system. Taking a user-centered design approach should optimize a computer system's usability,"

emphasizing the interface/interaction focus and the systems (automation) usability. Parasuraman and Wickens (2008) state that HCA depends on consideration of two meta-components

- the functionality (technical realization) and
- the interface (design and the corresponding interaction principle).

In DIN EN ISO 9241-210 2010, HCD is described as an iterative process, recursively improving or enhancing the understanding and definition of context of use, user (operator) requirements, developing of prototypes, and their evaluation (refer to Fig. 2.10).

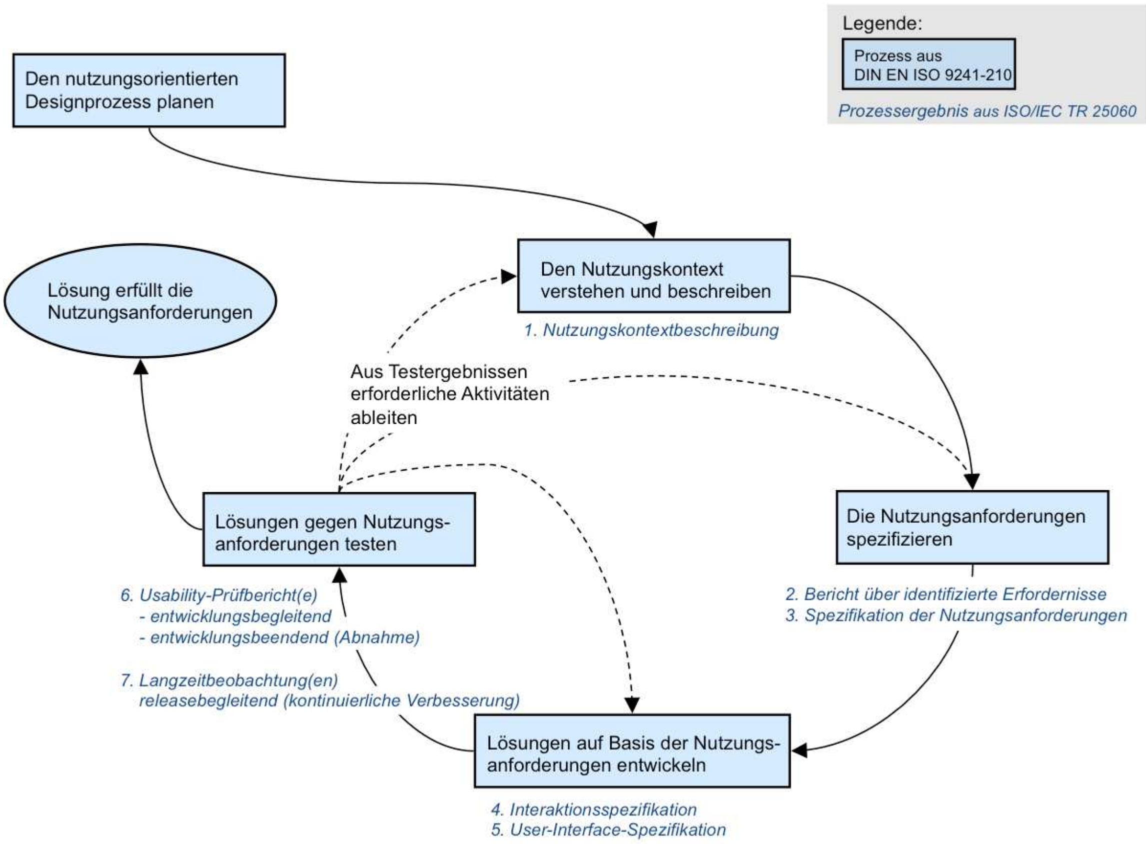


Figure 2.10 – User-centered design process according to DIN EN ISO 9241-210 (2010)

Goodrich and Boer (2003) support the importance of observing human operators perceiving their environment and realize prototypes such that reasonable expectations are facilitated. Manage automation to meet human operator expectations is one of the declared goals of HCD. Aligning human operator and automation initiates a paradigm change shifting the view to HAS into the reverse direction. As introduced earlier, "technization" of human is the first attempt of harmonizing HAS during the first phase of automation as mentioned before, which is in HCD not popular anymore. Tzafestas (2009, 2010a,b) describes "humanizing" of automation as principle of HCA. Thereby, "humanizing" means

> "all decisions for design and construction of the automation systems are made so as to meet, to the maximum extent, the humans' intentions and preferences in achieving the goals for which they are responsible."
>
> – Tzafestas, 2010a

Goodrich and Boer (2003) refer to this as using the human operator "as template for automation" according to human skills.

Sheridan and Parasuraman (2005) summarize some criteria of HCA and add statements to challenge them (refer to Tab. 2.2) and ask whether the solution is appropriately addressing questions of HCA. Following the proposed HCD principles contributed by Riera and Debernard (2003), HCA is achieved by accounting the following facts.

1. The main objective is the improvement of the global performance of the HMS and not only the technical system.

Table 2.2 – Criteria of human-centered automation (HCA) according to Sheridan and Parasuraman (2005)

Nr.	Criteria	Remark
1	Allocate to the human the tasks best suited to the human, and allocate to the automation the tasks best suited to it.	Unfortunately, there is no consensus on how to do this; nor is the allocation policy necessarily fixed, but may depend on context.
2	Keep the human operator in the decision-and-control loop.	This is good only for intermediate-bandwidth tasks. The human is too slow for high bandwidth and may fall asleep if bandwidth is too low.
3	Maintain the human operator as the final authority over the automation.	Humans are poor monitors, and in some decisions it is better not to trust them; they are also poor decision makers when under time pressure and in complex situations.
4	Make the human operator's job easier, more enjoyable, or more satisfying through friendly automation.	Operator ease, enjoyment, and satisfaction may be less important than system performance.
5	Empower or enhance the human operator to the greatest extent possible through automation.	Power corrupts.
6	Support trust by the human operator.	The human may come to overtrust the system.
7	Give the operator computer-based advice about everything he or she should want to know.	The amount and complexity of information is likely to overwhelm the operator at exactly the worst time.
8	Engineer the automation to reduce human error and minimize response variability.	A built-in margin for human error and experimentation helps the human learn and not become a robot.
9	Make the operator a supervisor of subordinate automatic control systems.	Sometimes straight manual control is better than supervisory control.
10	Achieve the best combination of human and automatic control, where best is defined by explicit system objectives.	Rarely does a mathematical objective function exist.

2. Consequently, induced effects of the artifact must be taken into account. For that purpose, the HMS is studied, taking into account human characteristics as well as technical aspects.

3. Alternative approaches to technical centered automation must be proposed. Human-machine cooperation and dynamic tasks allocation are examples of solutions.

4. After the design of the HMS including a human-machine cooperation is achieved, an evaluation step is needed involving technical as well as human criteria. The latter are difficult to perform due to the lack of "observability" of human operator's cognitive behavior.

However, Sheridan and Parasuraman (2005) state that there is no measure of quantifying the suitability of the above statements, making an evaluation of successful HCD complex.

A more global view to HCA is contributed by Boy (2011). The Artifact-User-Task-Organization-Situation (AUTOS) pyramid evolved from simpler geometric patterns as framework to describe HCD approach principles according to a discrete entity (refer to Boy, 1998, 2011). The different entities,

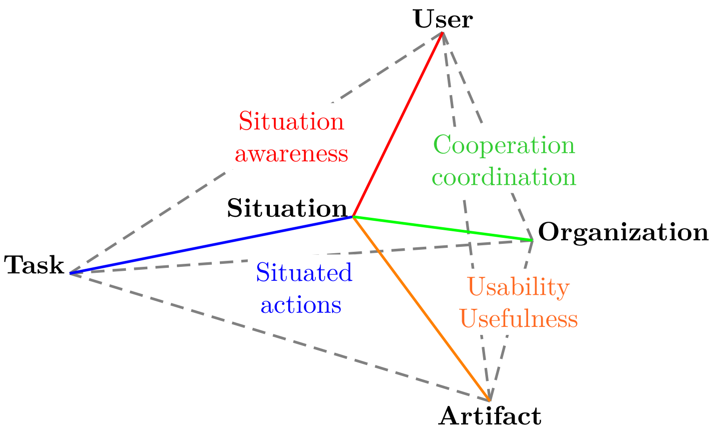


Figure 2.11 – AUTOS pyramid according to Boy (2011)

- artifact (system to be designed human-centric, automation),
- user (equals human operator depending on the domain),
- task (to accomplish whether individually, in collaboration, or automatic),
- organizational environment (as typical constraints to the task, design), and
- situation (corresponding to the operation mode, such as emergency or regular operation)

are representing a construct to rationalize the relations within HCD - refer to Fig. 2.11. Using the AUTOS pyramid, issues of HCA can be deduced along its dimensions, such as

- Situation awareness (SA) connecting user, task, and situation (refer to 2.4.2),
- situated actions based on task, artifact, and situation,
- usability provided by artifact, organization, and situation, and
- cooperation enabled by organization, user and situation.

Other authors define HCD, HCA respectively, as most likely adaptive automation (Hancock et al., 2013; Sheridan and Parasuraman, 2005). Endsley and Kiris (1995) state that

> "more work is needed to explore techniques such as these [e.g. adaptable task allocation] in order to establish HCA that maximizes overall human-system performance."

Thus, task allocation is one popular and widely treated HCA principle promising advantages for e.g. shop floor automation (Lindström and Winroth, 2010) that is detailed in Section 2.4.1. According to Parasuraman and Riley (1997), adaptable automation is to provide the remaining decision of using or not using automation to the human operator (Parasuraman and Riley, 1997).

2.3.2 Useware & Usability engineering

As stated in the definition of automation and the quotation in Section 2.1.1, HCA is usually seen as how to design control devices and displays in control rooms as well as the technical

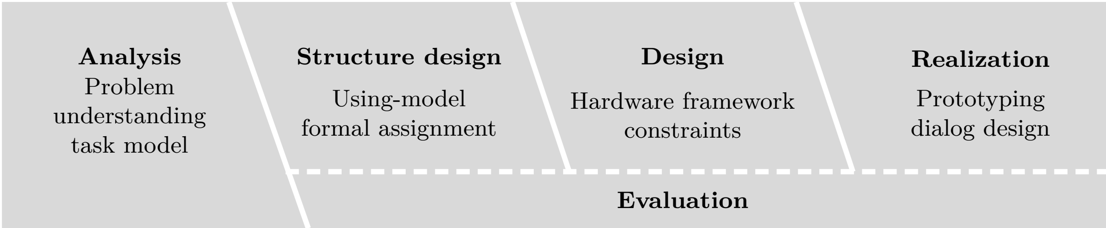


Figure 2.12 – Useware development process according to Zühlke (2012)

process behind, so that human operators feel comfortable in executing their duties efficient (which can be seen as place holder for any other benchmark). Reaching the defined benchmarks in automation disciplines by applying HCD means gaining benefit from both domains, human and automation, with the side effect of advanced flexibility paired with ease-of-use.

Earlier, usability is treated out of context of issues, meaning the actual context of work with respect to physical actions and the environment. The assignment of solving the problem of user's satisfaction is addressed by interface designer's that build prototypes isolated from context and thus, cannot consider usefulness in parallel. Hoffman et al. (2002) criticize that usability is seen as part of HCD manifested in only the software engineering process. Corresponding usability testing is performed on purpose the user's satisfaction rather with the interface design than with the overall design of interface and interaction design. Clemmensen et al. (2010) agree that separation of interface design and software implementation is likely to build a barrier to human operator, even though the interface design is evaluated with end users. Because of the strong interconnection of "visual presentation" and "interaction behavior" enforces the cooperation of involved entities.

Today, detailed usability testing, evaluation, or studies are common practice, however often applied in the final step of a design. In contrary, modern usability engineering focus on the usability evaluation throughout the development process. Zühlke (2004) as one example developed the method of useware engineering that includes the HCD approach for an advanced usability improvement in the early development stage of new products or processes, as well as for HMS.

In Fig. 2.12 the overview of a usability-oriented design process is illustrated. Zühlke (2012) defines the useware development process into four sequential and one parallel evaluation stage (which is central). Essential to achieve a good result by usability engineering, is the in-process user evaluation. Still, common practice is to integrate users into the final stage, which may end with higher amount of design iterations compared to the proposed usability development process.

"Usable" systems are defined in different ways. Citing Kushniruk and Patel (2004) and Rogers et al. (2002), usability is defined "as the capacity of a system to allow users to carry out their tasks safely, effectively, efficiently, and enjoyably". Thereby, questions of

- how easily a user can carry out a task using the system,
- assessing how users attain mastery in using the system,
- assessing the effects of systems on work practices, and

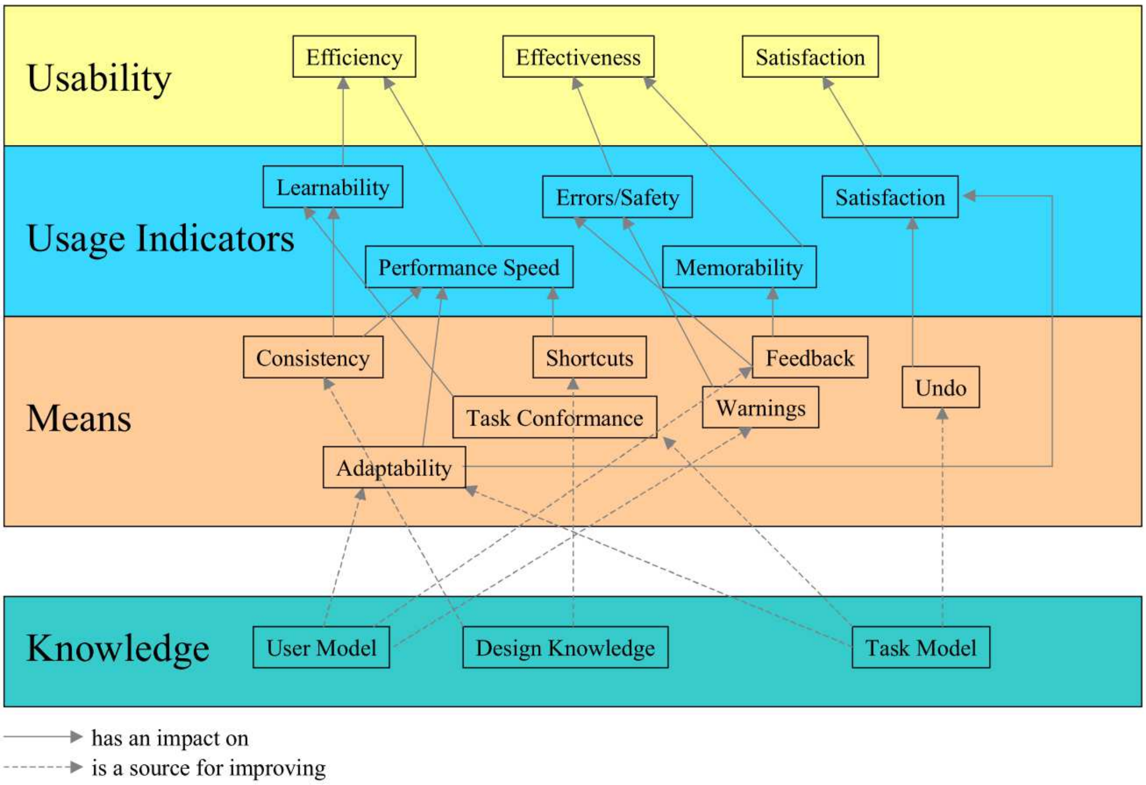


Figure 2.13 – Layered usability framework
according to Veer and Welie (2003) and Welie et al. (1999)

- identifying problems users have in interacting with systems

are concentrated on to be solved during the development phase. This leads to a prototype that aligns with the user's satisfaction. According to Kerren et al. (2007) user satisfaction can be decomposed in

- effectiveness, representing the accuracy and completeness with which users achieve certain goals,
- efficiency as the relation between the accuracy and completeness with which users achieve certain goals and the resources expanded in achieving them, and
- satisfaction as the user's comfort with and positive attitudes towards the use of the system.

Hence, the result of usability engineering leads to a satisfied user that is able to solve a defined task completely without difficulty or frustration, and meanwhile does not use more (cognitive and physical) resources than expected.

A framework relating the user's satisfaction to means, usage indicators, and the usability is illustrated in Fig. 2.13. The framework is designed due to the fact that the three common aspects, efficiency, effectiveness, and satisfaction (according to DIN EN ISO 9241-210 2010), are abstract and not adequate for solving usability issues in practice. This highest level of usability is affected by usage indicators that can be observed in experience or quantified by measurement. Improving usage and achieving better usage indicators can be realized by adjusting means that are similar to interface aids or design improvements. Source of such improvements can be delivered by the knowledge of user, design, or task. Thus improving usability can be tracing an observed usage indicator to means and taking the corresponding mean into consideration but also to the knowledge model and improving the models of e.g. task and user in un-described parts. Kulyk et al. (2007) contribute an overview of a comparable set of usability concerns that are actually addressed in varying intensity and without distinguishing between the different layers.

Table 2.3 – Aspects of usability according to Kulyk et al. (2007)

Aspects/Definitions	Bennett, 1984	Gould and Lewis, 1985	Nielsen, 1993	9241-210[3]	Quesenbery, 2003
Effectiveness		●	●	●	●
Efficiency	●		●	●	●
Satisfaction	●	●	●	●	●
Ease of learn	●	●	●		●
Flexibility	●				
Ease of remember		●	●		
Ease of use		●			
Error tolerance					●

Hoc (2000) states that usability is an issue of transparency throughout the design process. However, the user is often only using a "window" to the system to interact, meaning even the window needs to disclose the necessary usability related facts. Recapturing the "window" metaphor is especially true as still in HCA, supervisory control is seen as effective role for the human operator. Referring to Cacciabue (2004), the system designer is in charge of balancing concepts of supervisory control, user-centered design, and system's usability to achieve an effective HAS with a corresponding interface.

As referred above, user centricity in automation is meant to focus on the variety of involved disciplines and incorporate users as soon as the development process starts. In HCA, user centricity is often reduced to interface design and interaction design (but not especially haptics) in parallel to adaptable task allocation. Sheridan and Parasuraman (2005) summarize Grice's axioms/rules with respect to designing user-centered interfaces for adaptable task allocation as:

1. Make many conversational moves for every error made.
2. Make it very easy to override and correct any errors.
3. Know when you are wrong, mostly by letting the human tell you.
4. Do not make the same mistake twice.
5. Do not show off. Just because you can do something does not mean you should.
6. Talk explicitly about what you are doing and why.
   (Your human counterparts spend a lot of time in such meta-communication.)
7. Use multiple modalities and information channels redundantly.
8. Do not assume every user is the same; be sensitive and adapt to individual, cultural, social, and contextual differences.

[3] DIN EN ISO 9241-210 2010

9. Be aware of what your user knows, especially what you just conveyed (i.e., don't repeat yourself).
10. Be cute only to the extent that it furthers your conversational goals.

In this context adaptable task allocation between human and automation (agent) in combination with the human operator being supervisory controlling the HAS is seen as the major aspect of HCA (e.g. refer to Cacciabue, 2004).

The variety of approaches on user centricity in HMS, to which the above paragraphs are only referring to a few concepts without claiming to be complete, reflects the way future automation is seen. Thus, human centered approaches evolved from the historic view of completely manually work, over full automation in the early beginning, and these days back to questions of optimal alignment of human and automation in HAI (referred to as semi-automated HAS).

2.4 Semi-automated human-automation-systems (HAS)

In fact, automation still needs human intervention to a minimal but important fraction (Bainbridge, 1983; McKown, 1993). Spath et al. (2009) describe semi-automation as

> "work characteristic of a machine that only needs some degree of support from man. In contrast to a completely automated system, semi-automation does not achieve complete relief from work for the worker. The control of the individual functions is usually achieved by the technical system. Program control, which means the start, end, and succession of the individual functions, is accomplished by man,"

which implies that most of automation systems are rather semi-automated than fully-automated HAS. Bengler et al. (2012) state that in semi-automated HAS, such as driver-car or worker-automation, the human operator is guaranteeing safety of the system. Thus, the relationship between human operators (in their supervisory position) and the technical systems is subject to an optimization process with the interface in its functional and haptic design and a sophisticating task allocation as outputs.

2.4.1 Analysis and allocation of functions and tasks

Task allocation is a popular instrument of controlling the LoA and support the human operator by an adaptable interaction intensity. Essential and necessary prerequisite to achieve a sophisticated task allocation is the task analysis. Both, analysis and allocation are related to the application.

In order to set up a complete list of tasks, hierarchical (Diaper and Stanton, 2003) or sequential (Diaper and Stanton, 2003; Skinner, 1957) techniques are common and evolved from approaches that occurred parallel to the occurrence of Fitts' list. Having the list of (sub)tasks defined, specifications, logical conditions, and/or transitions between the (sub)tasks are added and the task allocation process starts with assigning (sub)tasks to agents (Tzafestas, 2010c).

Hierarchical task analysis (HTA) is a flexible tool that can be adapted to various application at any level of detail. Since there is no rigid method to follow, the analysis'

Table 2.4 – Principal steps in hierarchical task analysis (HTA) in accordance to Diaper and Stanton (2003)

Step number	Description
Decide the purpose(s) of the analysis	Design of system/interface/operating procedures/manning.
	Determine training content/method.
Get agreement between stakeholders on the definition of task goals and criterion measures	Stakeholders may include designers, managers, supervisors, instructors, operators.
	Concentrate on system values and outputs.
	Agree performance indicators and criteria.
Identify sources of task information and select means of data acquisition	What sources as are available? e.g. direct observation, walk-through, protocols, expert interviews, operating procedures and manuals, performance records, accident data, simulations.
Acquire data and draft decomposition table/diagram	Account for each operation in terms of input, action, feedback and goal attainment criteria and identify plans.
	Sub-operations should be (a) mutually exclusive (b) exhaustive
	Ask not only what should happen but what might happen. Estimate probability and cost of failures.
Re-check validity of decomposition with stakeholders	Stakeholders invited to confirm analysis, especially identified goals and performance criteria.
	Revert to step 4 until misinterpretations and omissions have been rectified.
Identify significant operations in light of purpose of analysis	Identify operations failing p×c criterion
	Identify operations having special characteristics, e.g. high work-load, requiring teamwork, specialist knowledge etc.
Generate and, if possible, test hypotheses concerning factors affecting learning and performance	Consider sources of failure attributable to skills, rules and knowledge.
	Refer to current theory/best practice to provide plausible solutions.
	Confirm validity of proposed solutions whenever possible.

result is depending on the effort and the attention of the analyst(s). According to Tzafestas (2010c), the HTA' benefits as well as their reliability and validity are proportional to this effort. General steps that guide analysts through an HTA are illustrated in Tab. 2.4.

Boy (1998) differs task analysis into two possible procedures

- goal-oriented and
- event-oriented

task analysis. The goal-oriented approach is similar to HTA and decomposes hierarchically goals into sub-goals until a level of basic actions is reached. In contrary, the event-oriented task analysis is concentrating on the context of an action. Thereby, similar to goals and sub-goals, the context is incrementally decomposed into sub-context until a level of situated actions is present. In Tab. 2.5 the comparison of the top-down and bottom-up approach is illustrated that on the one hand focuses on the goal space and on the other hand on the context space to consider tasks in a HAS.

Table 2.5 – Goal- vs. event-oriented task analysis in accordance to Boy (1998)

	Goal-oriented task analysis	Event-oriented task analysis
Human behavior models	Intentional and deliberative	Reactive and explicative
Approach	Top-down based on analytical descriptions	Bottom-up based on cooperative observation protocols and interactions with users
Modeled process	Internal model of an agent	Interaction between several agents
Goal space	Strongly defined, limited by the granularity of the description	Loosely defined
Context space	Loosely defined	Strongly defined, limited by the granularity of the description

Early work on task allocation with respect to the agent's (human or automation) individual strength is performed by Fitts' list in the early 1950's. Fitts et al. (1951) reduce differences of humans and machines into a static list illustrated in Tab. 2.1. Even though, there are also discussions related to inflexible task allocation, the principle intention of Fitts' list is answering the question of what to automate in HMS. Especially, Hoffman et al. (2002) point out that rigid task allocation according to Fitts is limited and thus, Hoffman is referring to the "un-Fitts" list synthesized from Woods media content[4]

Another popular contribution to task allocation is published by Rouse (1991) and recently reviewed by Inagaki (2003). Here, task allocation is analyzed with respect to automation strategy and subdivided into categories, such as

- comparison allocation,
- leftover allocation, and
- economic allocation.

Comparison allocation is similar to the approach of MABA-MABA. Human operators and automation are seen as agents that offer resources with a certain capability. Relative capabilities of the human operator are compared to those of the automation. The tasks are allocated to the agent (either human or automation) having the appropriate capability. Leftover allocation is an approach of maximizing automation. All tasks are automated that are technically automatable and a suitable automation technology is available. The remaining (leftover) tasks are assigned to the human operator. Economic allocation can almost be seen as leftover allocation with the side constraints of automation cost and labor. The result of the optimization of costs leads to an allocation of tasks to the most economic agent (either human or machine). Combining comparison and economic allocation is the approach of Chao (2009). Chao (2009) allocates tasks according to their action characteristics and with respect to a suitable work mode of the human operator.

In contrary to inflexible task allocation, adaptable task allocation means evaluating the assignment process not in the pre-implementation but during operation. In literature, this

[4] – (last visited October 4th, 2014)

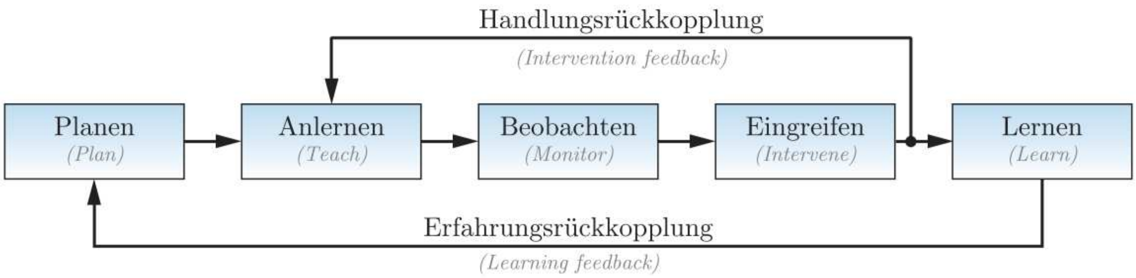


Figure 2.14 – SHERIDAN's five stages supervisory architecture according to Tzafestas (2009)

is also referred to dynamic task allocation (refer to Delft and Schraagen, 2004; Hollnagel, 2003). However, authority and responsibility transfers between human and automation are complex processes and thus of central interest (Flemisch et al., 2012). This issue is often solved leaving the task allocation authority to the human operator, who can dynamically decide whether to take over additional tasks or leave the assignment to the automation. A human-centered architecture for implementing delegation function in supervisory interfaces is e.g. published by Miller and Parasuraman (2007). Miller and Parasuraman (2007) use the playbook metaphor known from documented (approved) plays of sports teams, to implement an architecture for delegating tasks in supervisory controlled HAS.

According to Mattsson et al. (2012), task allocation is categorized as an automation-centered approach in describing interactive HAS. In this case common practice is the principle of leftover automation. This leaves decision and supervisory functions to the human operator, which are in turn designed most likely human-centered. However, even in comparison automation, supervisory control approaches are valuable to design the overall HAS human-centric.

2.4.2 Supervisory control in automation

Supporting human operator in supervisory control is a classical research field as it is seen as key issue in HAS science (e.g. refer to Cacciabue, 2004; Lindström and Winroth, 2010; Säfsten et al., 2007; Skjerve and Skraaning Jr., 2004; Winroth et al., 2007). Johannsen (1993) refers to supervisory control as prevalent interaction concept in HAI consisting of five stages (refer to Fig. 2.14). The human operator's task within this supervisory role is to (Sheridan, 2006)

- plan the next action (Plan),
- provide information to the automation that is prerequisite to the planned action (Teach),
- trigger the action and monitor the automation process during execution (Monitor),
- intervene if some irregularity occurs (Intervene), and
- evaluate the performance to improve the behavior from observed experience (Learn).

Sheridan and Verplank (1978) categorize HAS into ten levels of (supervisory controlled) automation. According to Tab. 2.6, semi-automation is the major segment of automated HMS. The interaction of human operator and automation in supervisory control role is strongly connected to exchange of information. Parasuraman et al. (2000) refer to four phases of information processing in HAS

Table 2.6 – Levels of automation (LoA) in relation to the information processing levels in accordance to Kaber and Endsley (1997), Parasuraman et al. (2000), and Sheridan and Verplank (1978)

LoA	Description	
	Automation...	
1	offers no assistance: human supervisor must do it all	manual
2	offers a complete set of action alternatives, and	
3	narrows the selection down to a few, or	
4	suggests one, or	
5	executes that suggestion if the supervisor approves, or	semi-automated
6	allows the supervisor a restricted time to veto before automatic execution, or	
7	executes automatically, then necessarily informs the supervisor, or	
8	informs him after execution only if he asks, or	
9	informs him after execution if the subordinate decides to	
10	decides everything and acts autonomously, ignoring the supervisor	fully automated

1. information acquisition,
2. information analysis,
3. decision selection, and
4. action implementation

that are continuously passed through. Improving design of the interface and creating abstract visual representatives of information can positively affect information acquisition and analysis (refer to Kaber et al., 2007; Kerren et al., 2007). Decision selection is supported by adding decision support aids and simplification of input of action sequences (Lehto and Nah, 2006) or of delegation tasks (Miller and Parasuraman, 2007).

An additional and also important issue in supervisory controlled HAS is the fact of loss of skills or skill degradation, when the human operator is not adequately integrated in the system and its role is strictly reduced to monitor an almost perfect automation. In this case, the given bandwidth of information exceeds their capability of information analysis and corresponding decision selection as it decreases over time.

Endsley and Kiris (1995) refer to this issue as taking the human operator "out-of-the-loop", which has a negative effect to the human operators understanding of the automation state. The term situation awareness is originated in the cockpit domain and is defined as

> "the perception 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 the near future,"

which is an essential process in supervisory controlled HAS. When human operators lose their SA, especially their ability to plan actions is affected. Thus, SA is intended to describe and explain erroneous behavior of human in HAS in commercial aviation accidents.

2.4.3 Examples from application domains

As illustrated in Tab. 2.6 and described in the aforementioned sections, most HAS can be classified as semi-automated HAS. Depending on the domain of origin of the HAS, the research focus varies. An excerpt of popular domains of HCA are

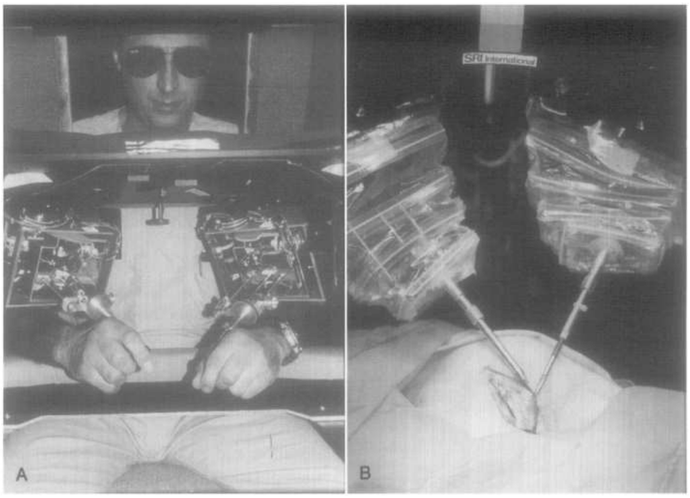
- aviation domain,
- hospital domain, or
- robotics domain.

In **aviation**, cockpit automation is widely treated to improve safety and reliability of aircrafts by supporting the pilot in various tasks and operations. Utmost popular is the aircraft's autopilot, automatic starting and landing, or automatic altitude control. In all cases, the human pilot is monitoring the state of the aircraft as the final authority. Historically, cockpit automation can be treated as origin of HCD. In Fig. 2.15, the historical change in cockpit design is illustrated. Research fields are fully-autonomous flight that is already realized with UAV. However, questions of how to design the cockpit frequently arise to which still no final answer exist. Glussich and Histon (2010) analyze severe accidents in cockpit domain that are subject to automation-induced accidents. Most of the analyzed accidents can be explained by the approach of SA. Furthermore, automation emerges from the pilot's cockpit to air traffic control centers, seeking for remote-controlled aerial transportation in future. In both cases, questions of SA are of central interest in order to satisfy safety and reliability requirements of tele-operated aerial systems such as airports.

In **hospital automation**, the research focus lies in automated hospital management or decision support (Niemann and Eymann, 2008), in robotic-supported surgery applications (Garg et al., 2013), or related life science applications (Kaber et al., 2009). Deb and Pal (1995) show an approach of tele-presence surgery that addresses issues in the competence availability in hospitals at different locations or in areas with reduced infrastructure (also treated in Capri et al., 2007). Bowersox et al. (1996) illustrate an early design of a tele-operated surgery system (refer to Fig. 2.16a) with haptic kinematic interface to control the surgery robot and visual (video-based) feedback to the surgeon.

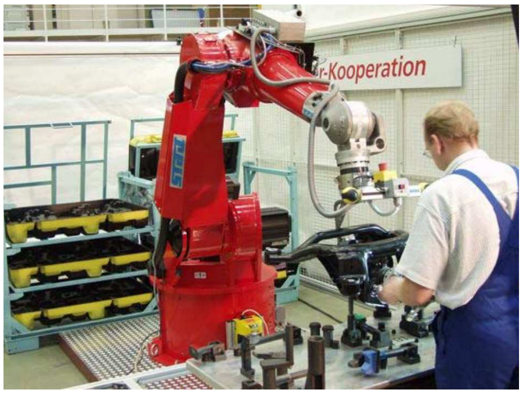
Mariappan et al. (2010) contribute work on flexible robotics, remote monitoring of patients for tele-medicine allowing doctors to adapt video feedback to the area of interest in tele-surgery systems. Similar work is done in the field of tele-mentoring that is also supporting the competence availability (Moore et al., 1996). Other research fields are minimal invasive surgeries that are supported by robotic surgery equipment such as illustrated in Garg et al. (2013) or image-guided surgery (Beaulieu et al., 2008).

Figure 2.15 – Development of cockpit design based on progress in automation (Photo: Rockwell Collins ©2013)



(a) Tele-presence surgery system (Photo: Bowersox et al., 1996). A: Surgeon's workstation with 3D viewing screen and instrument handles. B: RSU with manipulator arms.

(b) Collaborative surgery system (Photo: EU-project ACTIVE 🌍)



(c) Collaborative assembly process (Photo: PowerMate – Schraft et al., 2005)

Figure 2.16 – Sample applications of integrated HAS

Cooperative **robotic assembly** is a key element of modern manufacturing. Thus, dynamic task allocation without human operator being actively involved in authorizing task delegations is a key research questions in collaborative working environments. In Fig. 2.16c, the realization of a cooperative manufacturing cell is illustrated. Schraft et al. (2005) in this work focus on security aspects of the flexible cell, whereby collaboration is approached by shared human-robot work in an assembly process.

Incorporating robots with cognition to handle tolerances (Mayer et al., 2011) or improve robot's ability of sensing human intention (Krüger et al., 2009) are additional research scopes.

2.5 Chapter summary & concluding remarks

The clear separation of automation designers and users (human operators) is not given anymore. User-centered design (refer to Section 2.3) approaches or use-ware engineering

(a) Upholstering (Photo: hausderstoffe)

(b) Tube welding (Photo: IPS GmbH)

(c) No-bake molding (Photo: IfG gGmbH)

Figure 2.17 – Examples of typical manual manufacturing processes

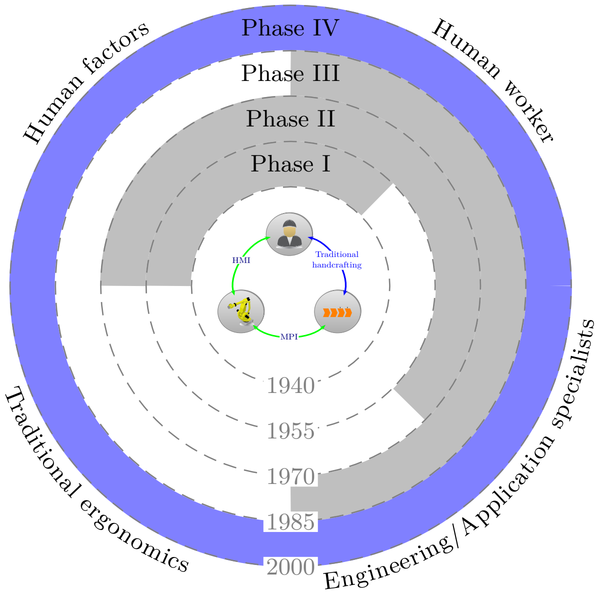


Figure 2.18 – Visualization of concentrations during the last decades of HAS design research

(Meixner et al., 2011; Zühlke, 2012) are dominant in present developments due to the fact that evaluation of HAS during early design phases is popular. The analysis of HAS evolved from completely manual work to full automation. The literature review shows that semi-autonomous HAS are promising with respect to their performance compared to fully manual or fully automated HAS (Kaber and Endsley, 1997). In order to describe semi-automated systems, terms such as task allocation are prominent. Frameworks to describe task allocation in HAS evolved from simple static lists (Fitts et al., 1951) to grades or levels of automation (Sheridan and Verplank, 1978) and are further detailed into dimensions of level and type of automation (Parasuraman et al., 2000). Further taxonomies are published that are similar to the LoA approach, however are detailed into different levels, such as Wandke (2005) separates the stage of action and the type of assistance.

In order to include human aspects in the development of HAS, researchers make use of analogies and metaphors to illustrate the way of thinking and acting of humans (or the assigned roles and related tasks). According to the analogies discussed by Nachtwei (2011), skilled employees in handcrafting processes can be seen as creative, reliable sources. Even though quality may vary (depending on the in-process feedback) and there is a certain level of individual rebuilding concerns (depending on the limited options how to resolve fabrication errors while fabricating) in the considered application of no-bake molding. Diversity of human operation leads also to diversity in interaction. Nachtwei (2011) proposes that analogies offer a wider view to classify human operators and provides operator classes based on recent literature. However, the question remains, how to reliable classify a human operator. In the considered application (handcrafting), the knowledge of employees is essential to keep process know-how within the HAS that is not documented at all. In such cases, comprehensive scientific analysis is not available due to a grown and over years developed manufacturing strategy that is refined by and over generations.

In Fig. 2.17, some representative examples of traditional handcrafting are given. Holstering, welding, and no-bake molding (detailed in Section 4.1) are typical examples that are not adequately addressed by the reviewed HAS research. These samples are characterized by strong interconnection of human skill and manufacturing process with the lack of in-process quality feedback. Thus, process quality measures can only be taken after process completion (e.g. comfort of upholstered chair, mechanical integrity of weld, or rigidity mold quality). Even though, the literature survey discloses that integral approaches (phase IV) are present in today's HAS research (refer to Fig. 2.18), the definition and the application of an integral automation chain to handcrafted processes while integrating human skills and experience within the resulting HAS are not treated in detail. The alignment of the different research fields, such as HAS modeling and simulation, engineering, human factors to form an integral approach to automate challenging handcrafting processes is an open research question as well as how to integrate human worker in the resulting HAS. This is especially important as typically human workers in handcrafting processes are not used to deal with automation systems.

Consequently, the question remains how to support human operators in their interaction with the created HAS according to their skills, knowledge, experience, and classification and if this individual support is reasonable. Here, formal approaches to describe HAS can be helpful.

Chapter 3

Formal modeling of human-automation-systems

As introduced in Chapter 2, the type of automation does not necessarily mean replacing human worker, rather automation aims a suitable combination of human intervention and automated actions leading to problems of process guiding and supervision. With the aim of developing and implementing process guiding and supervision assistance to human operators, formal modeling (=understanding) of HAS is used as an intermediary to combine participating disciplines. The idea behind is to apply a framework that is capable to represent the faced problem statement alongside with offering the ability to formulate analysis methods that can be applied to the framework. Formalizing HAS is challenging due to several contributing entities as already aforementioned. Descriptive methods to formulate machine characteristics such as time or frequency behavior are not suitable to represent interaction or even interfaces[1].

3.1 State-of-the-art modeling frameworks of HAS

Formal models are available for human skills such as decision making (Gilboa and Schmeidler, 2001) or reasoning (Nwiabu et al., 2012a), or even general human behavior (e.g. Rothrock et al., 2011) as an addition to process models, task models, or similar interfaces to contributing domains. As introduced in Chapter 1, this work focuses on the integration of human (and corresponding process experience) into a semi-automated process (originated by a manual molding process) using an unified approach to represent participating components of the HAS with a single description.

From the literature review of HCA in Chapter 2, the different influences of components are already illustrated. Formally, making further analysis to HAS on a component basis is also reasonable due to the clear separation of physical and controlling levels. According to Fig. 2.8, the system to be modeled consists of component models such as

- human operator,
- automation,
- process,
- interface,

[1]The content of this chapter is based on contributions already published (Fu et al., 2013; Langer and Söffker, 2010a; Langer and Söffker, 2011a; Langer and Söffker, 2012a,b, 2013, 2014; Soffker et al., 2012, 2010; Söffker et al., 2010a; Söffker et al., 2010; Söffker et al., 2011; Söffker et al., 2012a,b; Söffker et al., 2012; Söffker et al., 2013; Söffker et al., 2013b).

- interaction, and
- environmental constraints

that are also underlying relations and model specific interfaces and that are related to the systems physics and topology. Furthermore, human behavior models, task models, process organization models, goal models can be added to the overall HAS description. The level of detail is up to the intended purpose. In the considered work, the formal representation of the unified HAS description is utilized to serve as framework for process guiding and assistance. The proposed framework focuses on human operator, task, and interface models as there are of central interest. The automation model is not negligible since handcrafting is complex especially due to the presence of experience that is hard to be captured. However, the automation model is simplified to fit to the process model, which is in contrary analyzed in more detail.

Abstractly, human operators can be seen as an input-output system with sophisticated sensory, actuatory, and cognitive abilities. In handcrafting processes especially sensory and actuatory abilities are well developed and cognitive performance can be expected to be focused on application. Challenging is the functional or role mapping of handcrafting humans, when automation is included. Here, sense mapping and role substitution are essential descriptive tools to formulate and analyze the performed process. As aforementioned, role substitution is challenging with respect to the available technology. Especially in the domain of semi-automated HAS, roles are explicitly left to the human operator as their mapping cannot be performed with a required quality. Sense mapping is straight forward if appropriate technology is available, however understanding the physical principle behind the process and making this transparent in sensor measurements as well as designing an actuator from available technology that is handling the process the way it is designed, is the sophisticated part of semi-automation.

Modeling frameworks for HAS allow in general a simplified representation of sophisticated coherency. An available model supports e.g. the design process or evaluation (Curzon and Blandford, 2002, 2004). With respect to process guidance and supervision assistance, a framework including process, interfaces, and human operator is necessary that supports human operator in understanding the actual situation. Here, situation is meant as it is defined by the SOM approach published by Söffker (2008) and detailed in Section 3.2.1. In one phrase

> know your process (Langer and Söffker, 2012c; Söffker et al., 2013c),
> know your operator (Nachtwei, 2011), and
> know your options (Oberheid et al., 2011; Söffker et al., 2013a).

As introduced earlier, a variety of models exist capable to represent different components of HAS (refer to Fig. 2.8). According to the phrase above, a detailed algorithmic understanding of

- the physical (or technical) process (including e.g. sensors, actuators) and their relations,
- the human operator (as keeper and provider of process knowledge and skills) as well as
- interactions in between

is mandatory. To support human operators in semi-automated HAS and offer optional and necessary actions, the modeling framework must be based on a suitably precised knowledge base (or capture something comparable by training) and must offer the definition of task or goals.

The descriptions that are used within this thesis are elementary based on state automata or machines. The model of a state machine typically consists of

- input,
- state,
- output,
- state transition, and
- output function.

The state is defined by a set of state variables. A state transition is triggered by an event. The event is released by an input condition and additionally can be subject to pre-conditions. The consecutive state is determined by applying the input condition to the related function released (Moore or Mealy, Gill, 1962). The output function is used to determine the consecutive state.

The small number of descriptive elements of state machines makes the description fundamental (Lunze, 2006). In case a state machine is characterized by a finite number of states, it is referred to as Finite state machine (FSM). A distinctive feature of state machines is their separation into deterministic and non-deterministic state machines. The major difference is that the sequence of states in a deterministic state machine is fixed and can be fore-casted, however in a non-deterministic state machine the subsequent state is not predetermined. A widely treated example of a non-deterministic state machine is the dice; even under known initial conditions the resulting state[2] is unknown. Further detailed information of FSM are given by Gill (1962) or Lunze (2006) as well as analysis methods and modeling techniques are provided by Lunze (2008).

The (Enriched) labeled transition system (ELTS) (Combéfis et al., 2011) or MPSG (Shin et al., 2006) methods are capable of representing each of the three parts (human, machine, interaction). Combéfis et al. (2011) is focusing on the controllability given by the Labeled transition system (LTS) model of task, human, and interface meaning that the full-control property (Combéfis and Pecheur, 2009) holds all time. The MPSG approach of Shin et al. (2006) is based on a message exchange system, where human, interface, and process are communicating by sending and receiving messages, which is used earlier by Smith et al. (2003) to develop and implement a shop floor control application. Altuntas et al. (2007) concluded that the MPSG approach is not capable of a supervisory functionality that allows monitoring human operator interactions.

Wang and Liu (2008) published a Task-based model (TBM) to support the work flow in management processes. Here, the challenge lies in displaying the correct information at correct instance of time while pursuing a pre-defined, external triggered goal. Since this work flow assistance is related to low-level managing processes, the majority of modeling aspects come from the process and keep a complex process in correct order.

The EOFM language introduced by Bolton and Bass (2009) is a very formal and programmatic related (similar to XML) method to describe human, process, and interface. Interactions, tasks, and goals are defined based on physical input possibilities on an atomic

[2] excluding loaded dices

level. The approach shows flexibility in terms of real world interactive devices including pre- and post-conditioning, however projection for future states is not considered yet.

Apart from MPSG and Operator function modeling (OFM) methods, Finite state automata (FSA) are discussed by Kim et al. (2010) and Rothrock et al. (2011). Here, hierarchical FSA modeling is used as structural framework for analysis of system complexity and as basis for the investigation of human planning activities. This is realized by the psychological term of affordance to the human operator, whereby modeling of quantitative affordance is complex.

According to the statement above, knowing your process is a prerequisite of HAS-design and also essential with respect to assistance system design. Classical task analysis like HTA is used to achieve a profound understanding of a complex tasks. According to Shepherd (1998),

> "HTA is treated as a strategy for examining tasks, aimed at refining performance criteria, focusing on constituent skills, understanding task contexts and generating useful hypotheses for overcoming performance problems."

As the description induces, HTA is dividing a global task into to sub-task, and further into sub-actions that need to be accomplished in order to get the global task solved. The resulting tree-like structure is starting at the global task and is ending at finite actions. The structural illustration of elements contributing to the global task is a major benefit of classical HTA and allows the analysis of finite level actions as well as identification of possible improvements. Tan et al. (2009) extended classical HTA to consider task allocation (manual, automatic, and collaborative) in cell production. Benefits are discussed with respect to application-based requirements as total representation of operation, representation of operation collaboration for operation planning, safety development, and information support and performance evaluation. Especially, information support tends to a task-specific filtering and displaying of information to improve human operator interactions (refer to Section 3.3.3).

Extensions to classical task analysis such as HTA have been made for several reasons. In the domain of HAS, task analysis with respect to process guidance and assistance concepts is necessary. Paternò (2000) introduced ConcurTaskTree (CTT) in context to model-based interface design that enhances classical task analysis methods to deal with interconnections of tasks and associated context. An overview of the capabilities introduced by CTT in comparison to existing HAS frameworks are given in Tab. 4.1. The CTT is used to validate transferred interconnections that are detailed with respect to the underlying application in Section 4.1.2.

In conclusion, recently published contributions deal intensively with research and development in hybrid Human-automation-system (HAS) involving human operators (more passively than actively). The mentioned frameworks are not considering whether valuable process information nor available sensor and actuator information in order to provide assistance. Furthermore, human operator's input is seen as a pre-defined task (in some cases subject to pre-conditions) requiring a pre-defined solution that needs to be followed to accomplish the task. Within this representations uncertainties of components that need to be confirmed by measurement or by manual monitoring are neglected. A level of system abstraction results, where full automation will be the only logical consequence.

Also, several approaches dealing with the individuality and complexity of human operator interactions, goal-, and task-modeling exist. Unfortunately, the approaches are not address-

Table 3.1 – Comparison of operators among notations for task modelling (refer to Paternò, 2003)

	GOMS[a]	UAN[b]	CTT[c]	MAD[d]	GTA[e]
Sequence	•	•	•	•	•
Order independence		•	•		•
Concurrency		•	•	•	
Optionality			•	•	
Iteration		•	•	•	•
Allocation			•		•
Objects			•		•
Performance	•		•		•
Pre-post condition	•	•	•	•	•

[a] Goals, operators, methods, and selection rules (GOMS)
[b] User action notation (UAN)
[c] ConcurTaskTree (CTT)
[d] Methode analytique de description des taches (MAD)
[e] Groupware task analysis (GTA)

ing questions of improving Human-automation-interaction (HAI) by information filtering methods of available process information and corresponding supervision and guidance of complex, semi-automated processes. Initial process analysis serves as input to the HAS model, to the resulting physical design, and for corresponding process guiding and assistance functionalities (refer to Section 3.3) that are detailed in the following sections.

3.2 HAS model and assistance framework conceptual design

Recent interaction models for model-based, state-oriented, and event-discrete description of semi-automated (cooperative) processes are introduced by Message-based part state graph (MPSG) referring to Altuntas et al. (2007) and Smith et al. (2003) or (Enriched) labeled transition system (ELTS) referring to Combéfis et al. (2011) and Combéfis and Pecheur (2009). Considering the ELTS approach, the modeling concept is based on a pre-defined minimal, machine-based mental model that is completely known (by learning and training) to the operator ('full control property' refer to Combéfis et al., 2011). In difference the MPSG approach is using the state of the work piece (or considered part), identical to the state of the considered system, as representation. The state transitions (interactions) are triggered by messages that are exchanged between human operator and system.

In order to implement a state information-oriented assistance system to support human operators in their decision making process when dealing with semi-automated HAS, ELTS and MPSG are not suitable as only subsets of available state information are used for the description. In ELTS the state is marked by a pointer defined within the minimal mental model of the process. In MPSG the position of the considered work piece is located within the process model and used as state description. Both approaches are not capable to identify the actual process state by measurements or initiating routines based on the known (sensed) process information to support information filtering or offering user assistance that is also discussed by Nwiabu et al. (2012a).

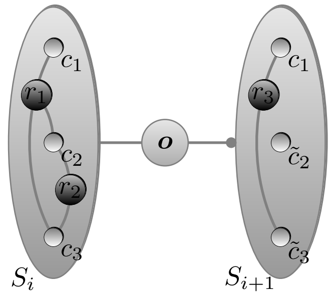


Figure 3.1 – SOM-representation of HAS based on Söffker (2008) (Langer and Söffker, 2014)

As framework for the implementation of user assistance systems addressing issues in detecting relevant information to support human operators, the Situation-operator-model (SOM) approach (Söffker, 2008) is used in specifically semi-automated scenarios. As application example a molding process using the no-bake technique is chosen, in which human workers need to be separated locally from the process to take into account human safety requirements and to achieve a repeatable process quality is chosen. Detailed information on the sample process is provided in Chapter 4.

3.2.1 Situation-operator-model (SOM)

The situation-operator-model (SOM) is proposed by Söffker (2001) to model human cognitive abilities alongside with technical processes in a single, uniform description. This allows human abilities like learning, planning, and acting as well as the description of human errors. Thus, the SOM description aims for the human operator being integrated in the HAS as part of the technical process.

From situations and operators

The realization is performed by mapping real world scenes to hybrid vectors called situations. A situation is representing the system state at a fixed instance of time and is revealing its inner structure by an unique set of descriptive variables (characteristics) including their optional connections (relations). Regarding a technical process, a situation is understood as the mapping of a (frozen, problem-oriented) process scene described by process variables (as characteristics). The graphical notation of the SOM methodology is illustrated in Fig. 3.1. Here, the gray-shaded ovals represent situations S_i and S_{i+1}. The white/gray-shaded circles depict characteristics c_{1-3}, whose internal relations constitutes by gray lines. The relations $r_{1,2}$ can stand for e.g. mathematical (Ordinary differential equation (ODE), Algebraic differential equation (ADE)) or algorithmic coherency of characteristics. Situation transitions are modeled by changing characteristics, relations, or a combination of both by applying an operator $\boldsymbol{o}$. An operator represents a real world action that can be performed automatically or is initiated manually. Manual initiation is related to human interventions that are interpreted as actions and correspondingly described by so-called operators. Operator can be simple minimalistic actions or complex actions consisting of several superimposed actions. In latter case, the resulting operator is referred to as meta-operator. A meta-operator is a combination of consecutive, microscopic changes to characteristics that is represented by a single macroscopic operation.

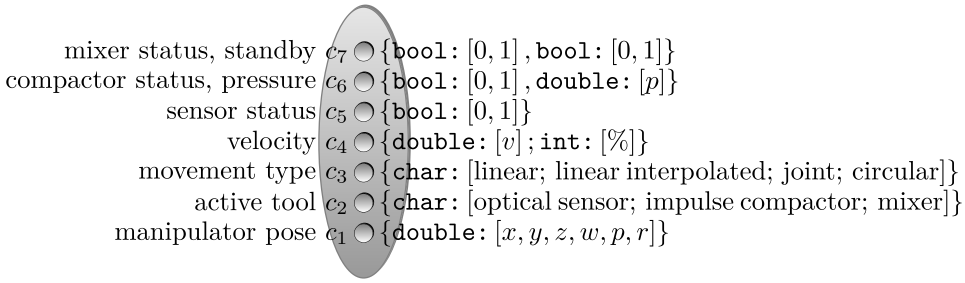


Figure 3.2 – Sample of a process describing situation vector (relations not shown) (Langer and Söffker, 2014)

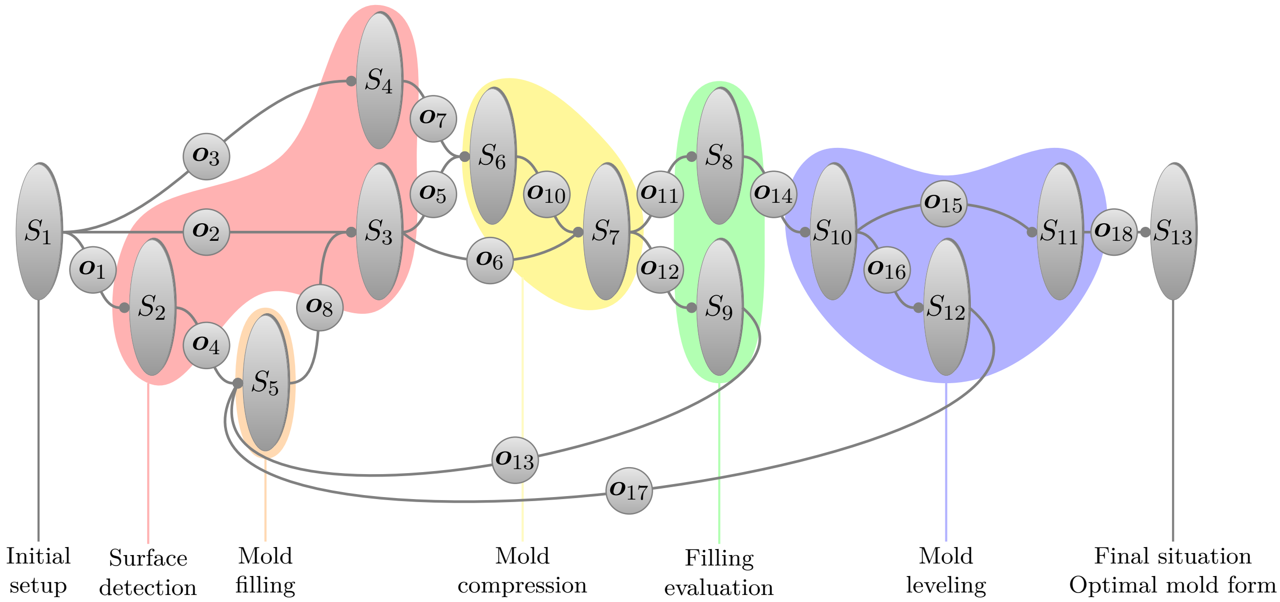


Figure 3.3 – SOM image of semi-automated molding process (top-level view) (Langer and Söffker, 2014)

In Fig. 3.2, a part of a situation (sub-situation) of the underlying application is shown that is used to describe the flexible semi-automated manufacturing system. A sub-situation can also be part of a situation vector, so present hierarchy can be modeled or a hierarchical structure is available. The illustrated situation is drawn neglecting existing relations due to clarity reasons, e.g. that a specific active tool enforces a mandatory movement type.

Regarding the set of operators offered by the considered HAS and all possible combinations of characteristic values and their possible inner structural relations, the complexity of HAS can be mapped to a discretized representation (refer to Fig. 3.3).

SOM-based action spaces

As previously introduced the SOM methodology forms situations out of characteristics and internal relations. Actions are triggered automatically or by human intervention and are described by operators. Starting from a defined initial situation (S_1) and applying

Table 3.2 – Set of characteristics for top-level description of semi-automated no-bake molding process (Langer and Söffker, 2014)

Characteristic		**Values**
Surface data	$c_{p,1}$	0: not available 1: available
Scan evaluation	$c_{p,2}$	0: not available 1: model 2: mold material 3: model and mold material
Filling	$c_{p,3}$	0: not available 1: performed
Filling evaluation	$c_{p,4}$	0: not available 1: low 2: high
Compression	$c_{p,5}$	0: not available 1: applied
Compression evaluation	$c_{p,6}$	0: not available 1: low 2: high
Leveling	$c_{p,7}$	0: not available 1: low 2: high
Leveling evaluation	$c_{p,8}$	0: not available 1: low 2: high
Process status	$c_{p,9}$	0: running 1: completed

all permutations of the available set of operators (independent of their trigger condition), leads to a network of interconnected situations that is defined as (complete) action space. Gamrad (2011) introduced action spaces based on the event-discrete SOM methodology of Söffker (2001) with the following definition

> “the term ’action space’ denotes a set of situation-action-sequences resulting from the propagation of alternative actions from a certain initial situation.”

Action spaces are also used by Oberheid et al. (2011) to identify optional actions while interacting in dynamic environments. Incorporating physical or technical constraints cancel out sub-branches that are unreasonable or impossible to reach during regular (and also irregular) process operation. The remaining network is seen as action space of the human operator (or the HAS) and serves as framework for user guidance and supervision assistance.

A reduced and reasonable action space of the underlying semi-automated process is shown in Fig. 3.3. This considered action space is based on a superficial situation vector that is shown in Fig. 3.2 and illustrates the top level view to the no-bake molding process with its different process stages that are discussed in Chapter 4. The corresponding list of characteristics and operators to construct the action space is given in Tab. 3.2 and Tab. 3.3, respectively. The resulting event-discrete representation is an image of all possible states of the considered HAS, as long as the assumption holds that all necessary process related information are turned into characteristics. This offers a problem-oriented modeling depth that scales the circumference of the action space to a requisite size and prevents the issue of ’model blow-up’.

Table 3.3 – Samples of defined operators of semi-automated no-bake molding process (Langer and Söffker, 2014)

Operator		Characteristics		Old value	New value
Surface measurement	o_1	Surface data	$c_{p,1}$	0: not available	1: available
		Scan evaluation	$c_{p,2}$	0: not available	1: model
Compression	o_6	Surface data	$c_{p,1}$	1: available	0: not available
		Scan evaluation	$c_{p,2}$	2: sand	0: not available
		Compression	$c_{p,5}$	0: not available	1: performed
		Compression evaluation	$c_{p,6}$	0: not available	2: high

With the assumptions above, process procedures can be mapped into the action space as sequences of situations and operations.

Modeling tasks and goals

Tasks and goals are seen as motivation for human interventions. Human interventions are important triggers in a semi-automated HAS. This means that human interventions are always intended to pursue a goal (or solve a task), that needs to be defined accordingly.

Here, task can be defined statically or dynamically as introduced in Chapter 2, whereas goal is meant to be a defined final situation to reach. Furthermore, the assumptions holds that human operators have a sufficient process understanding and a corresponding mental model that does not need to be exactly identical to the modeled action space but with small variations. With the given HAS model, the definition of goals is realized by defining situations to reach during process execution. This requires also an understanding (of the human operator) of the actual HAS status. This understanding is preceded by a situation perception and followed by projection of interventions to future states and can be aligned with the Situation awareness (SA) approach of Endsley and Kiris (1995) with

- capturing the current situation (measuring),
- localizing the situation within the action space (information assessment), and
- identifying the reachable situations (guidance assistance)

to reduce the set of possible and reasonable actions.

Having the process discretized in the action space and the manufacturing procedures mapped to sequences of situation and operators, assistance can be given to human operator while the manufacturing process is executed. The idea is that human operators are supported in normal operation mode to achieve the process goal and solve the task. However, if some irregularity occurs, the human operator is asked to provide process knowledge in order to solve the occurring problem.

Sophisticated user skills are necessary to perform well during handcrafted processes. So far, the action space represents the process, the human operator, and related interactions of the considered process. Tasks and goals are formulated by defining situations to reach or actions to perform. The SOM methodology allows to represent the theoretical background and is capable to describe the intended process guidance assistance. In order to implement the developed process guidance assistance, further frameworks are necessary that are capable of turning the applied functionality of the SOM methodology to a programming language that ideally can be used in a real-time environment. For the purpose of this thesis, the SOM methodology is not used in its full circumference as introduced by Söffker (2001). In order to have an unified framework representing process model, interface, and human interactions, the action space representation serves as descriptive tool of the overall HAS. The SOM offers more than the action space representation, such as implicit and explicit assumption, that can be used for enabling or disabling potential actions. However, for reasons of not restricting human operator actively, this potential advancement of interactive description is not used for the following human operator guidance approach rather human operator guidance assistance is based on providing essential and valuable information at correct instances of time.

3.2.2 Statecharts

Harel (1987b) introduced statecharts as visual representation to reactive systems and the problem of "exponential blow-up" that state transition systems have, when considering all possible states. Key benefits of statecharts compared to conventional state diagrams are additional AND/OR relations alongside with inter-level or concurrent component transitions and communication.

> "statecharts =
> state-diagrams + depth + orthogonality + broadcast-communication"
>
> – Harel (1987b)

In addition to typical elements of state diagrams (refer to Fig. 3.4a) such as states and transitions, statecharts consider

hierarchy that allows to assign super- and sub-states in a level fashion that is majorly reducing the number of transitions (Fig. 3.4b),

inter-level transitions allowing transitions between super- and sub-states and offering the ability of modeling in different levels of abstraction (refer to Fig. 3.4c),

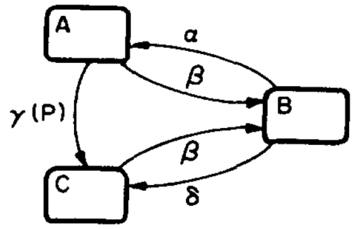
decomposition (e.g. orthogonality or parallelism) for having several sub-states. Parallelism (refer to Fig. 3.4e) means having two sub-states being active simultaneously. In contrary, orthogonality means the system to be in two non-intersective states that are alternatingly active during the iterative loop (refer to Fig. 3.4f) and indicated by areas,

history allows to keep a previously activated state when re-entering the corresponding super-state (refer to Fig. 3.4f), and

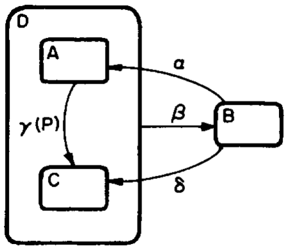
transitions actions , such as entry or exit actions or static reactions that are executed when entering, leaving, or staying in a state.

Further features distinguishing classical state diagrams from statecharts are triggers (and guards) that are initiated by events and allow for reactive system modeling. Especially in context of HAS modeling, triggers and guards are beneficial to implement assistance functions.

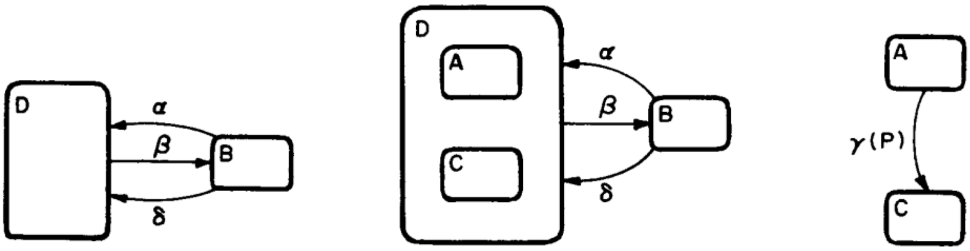
Until the introduction of statecharts, visual representation is not making use of a state vector, rather statecharts in the moment of occurrence use states as smallest item of description. Since statecharts are natively supported in the development environment, a state array collecting several variables is a fundamental descriptive element surpassed through all states and interface-able during all transitions.



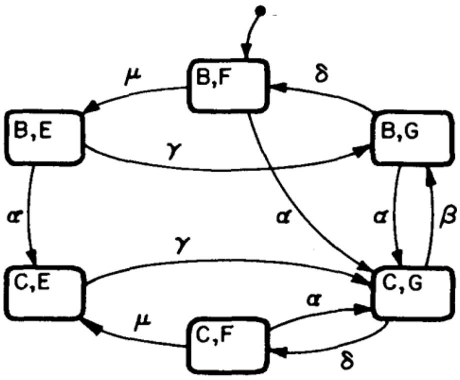
(a) Reference state diagram with the states (A, B, C, D), transitions ($\alpha, \beta, \delta, \gamma$), and a condition ($P$)



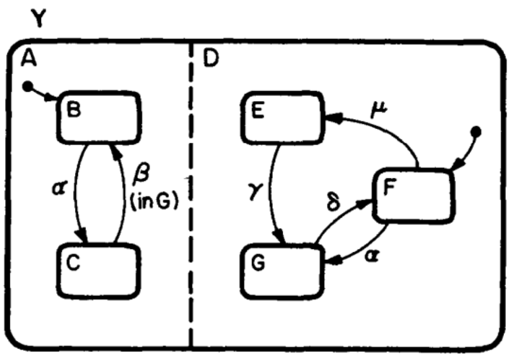
(b) Sample statechart with the superstate D, substates A and C, the state B, transitions α, β, and δ, and a conditioned transition $\gamma(P)$



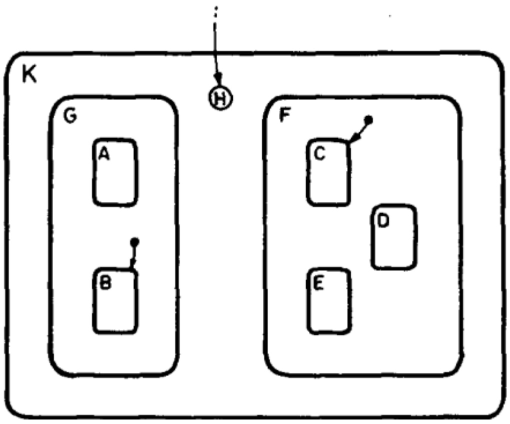
(c) Statechart decomposed into different levels of abstraction



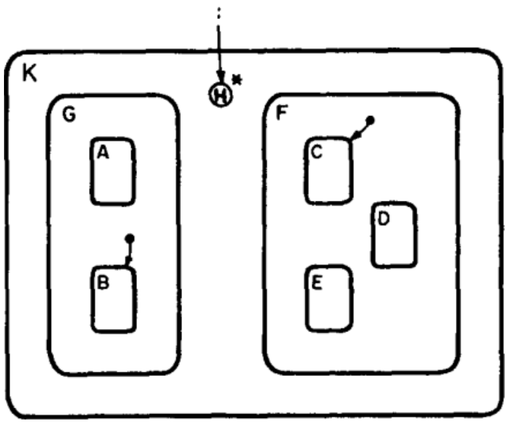
(d) State diagram with parallel states



(e) Realization of parallelism in statechart notation

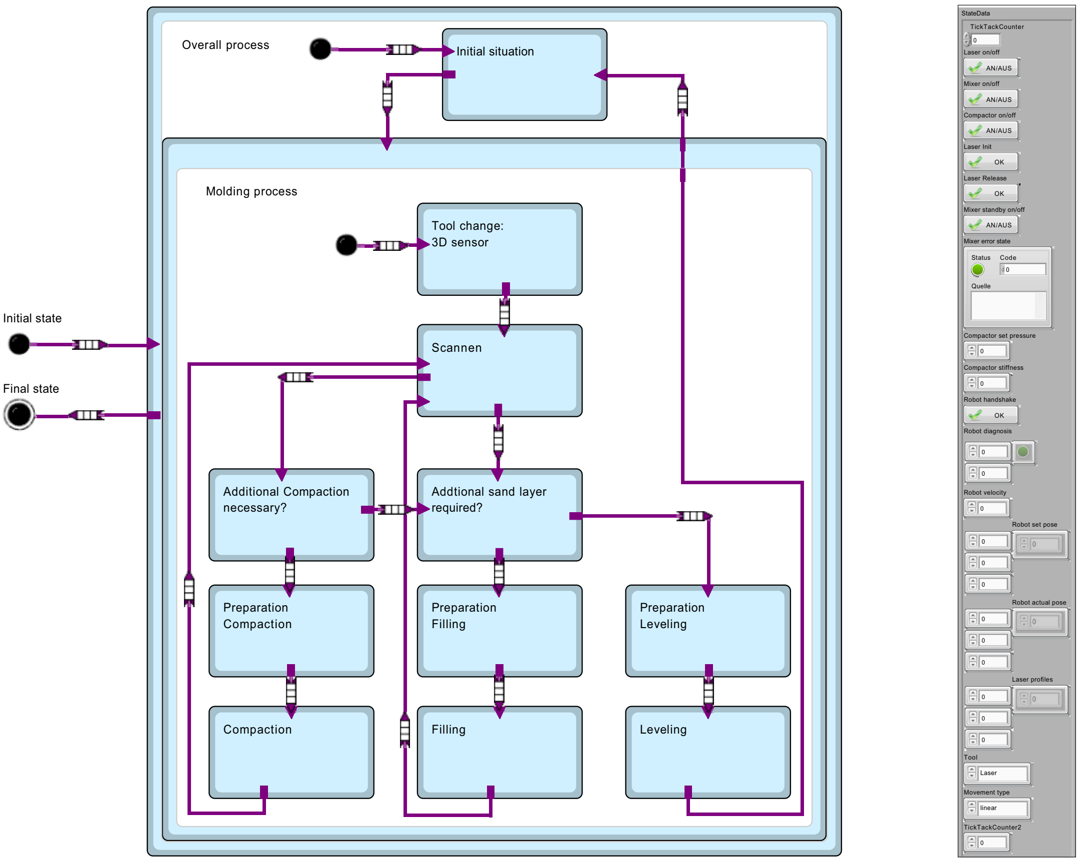


(f) History Ⓗ notation in statecharts



(g) History Ⓗ* notation in statecharts

Figure 3.4 – Statecharts notation according to Harel (1987b)



(a) Statecharts overview **(b)** State vector

Figure 3.5 – Statecharts implementation (using NI Statechart module)

A detailed description of the statecharts representation is discussed in Harel (1987a,b) based on a watch example. Further applications are published by Degani et al. (1999). In this example statecharts are used to represent state transitions and a corresponding assistance in terms of optimal planning in a manufacturing environment. Furthermore, statecharts are naturally supported by National Instruments (NI) LabVIEW software environment, which is used for the underlying application in this thesis (refer to Chapter 4). A corresponding sample statechart diagram is illustrated in Fig. 3.5 which is representing the underlying HAS of no-bake molding.

The way of modeling HAS using statecharts is similar to the SOM approach of the previous section, however statecharts are natively supported by the underlying development system. The HAS is modeled by defining

- inputs (controls),
- outputs (displays),
- state data (state vector), and
- diagram (statechart).

Inputs and outputs are representing the interface between automation and human operator and are linked to the physical Human-machine-interface (HMI). The state data collects all (state) variables that are necessary to describe the physics of the HAS. The diagram represents the state structure and transitions (similar to the overall process representation).

3.2.3 Comparison of SOM and statecharts

Both, SOM and statecharts philosophy differ from classical state description as both are defining states (situations) in a more detailed manner. The level of detail is supported by functions of sub-situations or hierarchy that reduce the risk of model blow-up, however this risk is still present. The approach of combining arbitrary data types to be combined to a hybrid state vectors is shared between both approaches, however major benefit of the SOM methodology is the ability to consider relations in between characteristics. This is an unique feature that has no alter-ego in statecharts methodology.

Major difference of statecharts and SOM is the way of dealing with transitions. In statecharts an event is triggering a transition that is applied as far as the guard is not preventing. In SOM an event is representing an operator, which is applied to the actual situation and is changing characteristics/relations in the way that is defined by the operator definition. Implicit and explicit assumptions can be seen as correspondence to guards.

Table 3.4 – Comparison of state automata, SOM, and statecharts

Elements	**State automata**	**SOM**	**Statecharts**
State	No explicit definition necessary	Hybrid vector (situation) collecting characteristics and relations	State data collecting state variables
State variables	n/a	Complex variable of an arbitrary data type, which can also include nested situations	Complex variable of an arbitrary data type, which can also include sub- and super-states or static reactions
Transitions	Input/output	Operator as complex function, can change characteristics but also inner structure and relations of a situation with implicit and explicit constraints	Initiated by triggered events with guards, constraints, and actions
Distinctive feature	Simplicity of state framework description	Capability of describing complex processes including features of hierarchy, cognition, structural changes by using relations in-between characteristics	Capability of describing complex processes including features of hierarchy, history, orthogonality (real-time ready)

In Tab. 3.4 a feature overview of SOM and statecharts in comparison to traditional state automata is given. Statecharts and SOM are capable of describing the overall process, interaction, and to include the human operator into the framework leading to an uniform description of the HAS. Even though SOM additionally considers human features such as cognition and learning that statecharts are not capable of, most features of SOM can be ported to statecharts, which have in turn the advantage of being natively supported by real time hardware. A pre-condition to use a statecharts-based framework to implement the proposed process control and assistance in semi-automated HAS is the ability to port SOM-based concepts to statecharts, which will be investigated in the following after having the guidance and supervision concepts specified.

3.3 Guidance and supervision concepts

Technical processes that are investigated these days often deal with semi-automated HAS (Breton et al., 2012; Fereidunian et al., 2007; Helldin and Falkman, 2012; Nwiabu et al., 2012b; Parasuraman and Wickens, 2008; Sheridan, 2011, refer to). These case studies confirm the value and the advantage of Human-centered automation (HCA) approaches (Fereidunian et al., 2007), detail challenges of their implementation (Helldin and Falkman, 2012), and identify recommendations to improve SA of human operators in complex environments.

Therefore, determining the relevant information (Breton et al., 2012) is an essential strategy to reduce human operator's input and thus allowing human operators to be focused when interacting with dynamical systems. Catching necessary attention and enhancing attention allocation by reducing the input set of information is essential to improve human operator assistance in semi-automated HAS. The combination of information collection, situation creation, situation identification, situation projection, and corresponding information filtering to support human operator's action selection process with a single descriptive modeling technique is still an open question.

3.3.1 Framework capabilities: action space-based process guidance assistance

As introduced in Section 2.4.2, SA in terms of user's understanding consists of

- acquiring data,
- comprehension of their meaning, and
- forecasting their change as time passes by (projection).

In Nwiabu et al. (2012a,b) a method merging SA approaches with Case-based reasoning (CBR) methods to Case-based situation awareness (CBSA) is introduced. The CBSA approach is used to predict user interactions while process execution and offers certain parallels to the proposed method. A case library is built, while user are interacting with the system and corresponding actions are captured. Both in combination is saved in a case-library, where retrieved situations (captured from the environment) are compared to, to project future situation by predicting actions based from the case library. With this approach a situation forecasting can be realized similar to the proposed action space-based method introduced in Section 3.3.3.

Pre-modeling of the HAS and the process itself means that an almost complete action space is available from the beginning on the interaction. In addition, characteristics are related to real world variables of arbitrary type that are measurable. The collection of measured characteristics forms the situation, that can be located within the given action space, and suitable actions for task completion can be detected. Meaning that an automated perception of the current situation, localization within the available HAS action space, and identification of potential options to pursue the current goal and thus deduced action selection assistance is given by the proposed SOM framework.

3.3.2 Technically implemented situation-awareness

Examples of technically implemented, automated SA are given e.g. in Ertle et al. (2012), Hasselberg et al. (2009), and Oberheid et al. (2011). Here, partial action spaces are established (simulated) beginning from the actual situation. From the given set of possible future states, an evaluation with respect to critical situations, actions, or beneficial options can be performed. This approach offers a deeper understanding of human operator interactions in complex, dynamical environments (Hasselberg et al., 2009) as well as an assessment of their decisions with respect to their possible (simulated) options (Oberheid et al., 2011). Furthermore, an evaluation of the safety status of a complex, technical system can be performed (Ertle et al., 2012). The overall system cognitive process and gained knowledge as well as collecting experience can be realized (Ahle and Söffker, 2008; Gamrad, 2011). In summary, the proposed SOM methodology allows the technical implementation of all the three phases of SA into a formal model of HAS. The connection between the formal model of the HAI and the HMI is the missing element. It will be a promising extension to improve the human operator performance of the HAS. Technically supporting the human operator's SA is only one side of the HAS interaction. The key element of a successful process implementation is to make the HAS status transparent and provide information of interest at correct instance of time.

3.3.3 Situation-based information filter

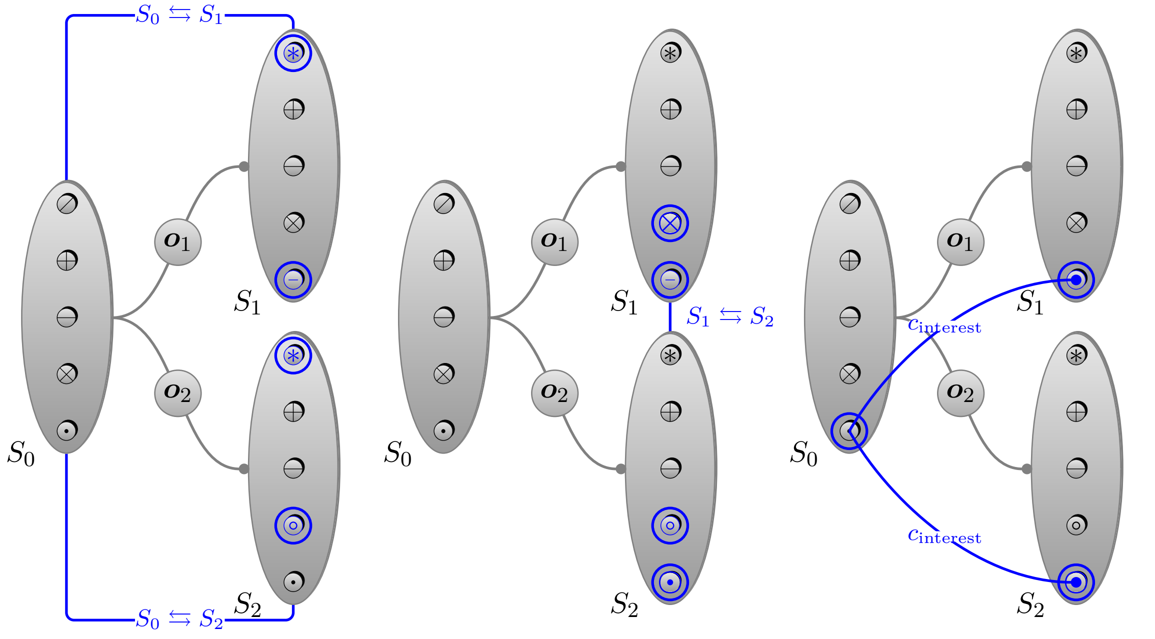
Providing necessary information at correct instances of time and in a sufficient and not overwhelming measure is a central idea of this contribution. Most important information retrieval is a complex question and is solved in literature e.g. by using the Choquet integral (DiVita and Morris, 2012). The integral evaluates criteria pre-defined by experts. Thus, the approach is not using a process model as its intention is to support human operators in critical events only and not consecutively.

In contrary to expert-defined criteria, the formal HAS model allows the extraction of information of interest on a logical level throughout process execution. Referring to Fig. 3.6, information highlighting can be given with respect to e.g.

- $S_0 \leftrightarrows S_{1/2}$: characteristic differences between initial and target situations (applicable if certain characteristics are changed by the available set of operators - Fig. 3.6a),
- $S_1 \leftrightarrows S_2$: characteristic differences between target situations (applicable if a complete set of characteristics is changed in a different way by the available set of operators - Fig. 3.6b), and
- $c_{interest}$: characteristic differences of predefined process quality-related characteristics (applicable if a process quality containing characteristic is changed by the available set of operators - Fig. 3.6c)

to be used for supporting the human operator in his/her comprehension (by illustrating reduced sets of information) and projection of the current process situation (by illustrating future situations).

Applying the method to the complete action space makes information of interest transparent throughout the modeled process. Similar to Nwiabu et al. (2012a,b), this method reduces the set of information and supports focusing on upcoming situations by process, task, or operator-related filtering. Furthermore, critical events as addressed in DiVita and



(a) $S_0 \leftrightarrows S_{1/2}$ **(b)** $S_1 \leftrightarrows S_2$ **(c)** $c_{interest}$

Figure 3.6 – Model-based information filter (preferred operator $\boldsymbol{o}_1$) (Langer and Söffker, 2014)

Morris (2012) can also be handled by this method, since the SOM-based approach allows to technically identify the actual situation within the overall HAS action space and based on the characteristic setup to evaluate the (security) states of the HAS.

Regarding the conceptual framework of SOM as tool to address issues in automated processes and with increasing amount of information available or easy to have, human operators can be supported in fulfilling their role in HAS. However, human operators are always understood as keeper of related process knowledge and of manufacturing skills that need to be considered within automation processes.

3.3.4 Visual technical process assistance

Technical process assistance can be realized by several methods, e.g. actively, passively or on different perceptual channels (audio, tactile, visual). In the considered application visual assistance is promising compared to other options (refer to Fig. 2.7). The reason lies in the environment of the HAS that is noisy and noxious. In consequence Personal protective equipment (PPE) must be worn all the time.

In this contribution visual assistance is given not to illustrate pure data sets only. The major difference is that visual assistance for process control of typically handcrafted processes with the side constraint that human operator are experts in handcrafting is not represented by data sets, but by a scene of the working environment. The scene display is used to integrate process activities (based on process knowledge) or product quality state (based on reduced information) that is introduced in the next section.

Summarizing recent development, there are still open questions in interactive HAS that need further refinement in formal modeling and corresponding application to typical HAS problems e.g. process guiding and supervision. The gap to be closed should solve the open question which information in which situation is necessary to support the human operator in the supervision role and provide adequate and situated input options to allow the human operator to react in time and in specific relation on the provided information with respect to the underlying process goal.

3.4 Chapter summary & concluding remarks

In this chapter, formal approaches are reviewed to describe integrated HAS and that are capably to realize this description in an uniform manner. The reason behind is that the conducted framework is subject to the proposed model-based information filtering method. Filtering information is essential in order to reduce amount of data to capture by human operators and to give decision assistance.

> "Information visualization is the use of computer-supported, interactive, visual representations of abstract data in order to amplify cognition."
>
> – Card et al. (1999)

The action space serves as graphical representation of the overall process that includes physical reasonable situations. From the action space perspective information of interest can be derived according to different introduced approaches, e.g. final situation differences, differences between initial and possible final situations, or based on the variable of interest approach. The discrete framework of interconnected states (situations) can also be mapped to a technical system, however not without losing methodical advantages. Statecharts are capable to represent the introduced model-based information filtering methods alongside with native support by the development environment.

Filtering information is one contribution to effective HAS, interface and interaction design are also important contributions in order the integrated HAS to perform properly. Both, interface and interaction design, are strongly related to the application and corresponding constraints that need to be incorporated.

Chapter 4

Application and implementation

> "Skilled workers historically have been ambivalent toward automation, knowing that the bodies it would augment or replace were the occasion for both their pain and their power."
>
> – Zuboff (1988)

Challenging applications for automation are handcrafting processes. Traditional handcrafting is characterized by working routines that evolved over decades. Without explicit documentation of fabrication skills, process knowledge is kept by transferring collected experiences over the generations of employees. A representative manufacturing process according to the mentioned experienced-based fabrication skills is the no-bake molding process that is applied to big cast parts that is introduced in the following[1].

4.1 No-bake molding process

No-bake molding belongs to sand casting techniques (refer to Fig. 4.1) in modern casting industry. The no-bake technique uses resin bonded sand that sets without additional heat and is usually related to an advanced product line-up combined by a small lot size. No-bake molding is a typical technique within the hand molding branch of lost-mold casting processes (Hasse, 2007). Characteristic to no-bake molding is that no thermal energy is needed to harden the mold. Solidification of the mold is achieved by adding furan resin (binding component) and phosphoric acid (catalyst, as in this case) in an appropriate relation to the quartz sand. As soon as the chemicals are mixed, the solidification reaction starts. Depending on the recipe, the mold material is plastically deformable, however some amount of mechanical compression energy is mandatory to achieve a certain mold rigidity prior to the solidification process to be finished. This molding technique is especially popular when dealing with big cast parts for which line production cannot economically be established.

These facts combined with the dimension of the cast parts (>100 tons) is disadvantageous regarding a full automation approach and explains the traditionally established handcrafting process. However, the technical ability to produce such big cast parts in a competitive quality is an unique feature of the considered casting companies. Problems in the traditional handmade process are on the one hand demographic issues and on the other hand protective regulations of employees with respect to the noxious environment. This leads to

[1] The content of this chapter is based on contributions already published (Fu et al., 2013; Langer and Söffker, 2010a; Langer and Söffker, 2011a; Langer and Söffker, 2012a,b, 2013, 2014; Soffker et al., 2012, 2010; Söffker et al., 2010a; Söffker et al., 2010; Söffker et al., 2011; Söffker et al., 2012a,b; Söffker et al., 2012; Söffker et al., 2013; Söffker et al., 2013b).

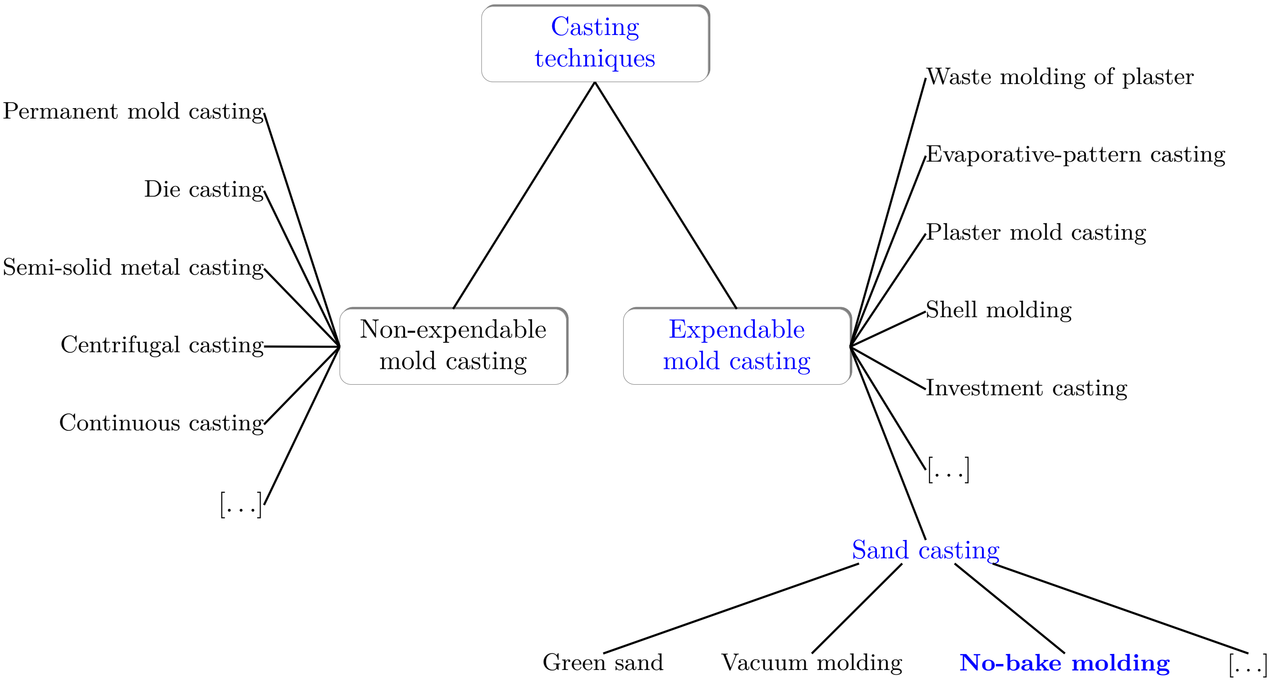


Figure 4.1 – Hierarchy of casting processes according to Hasse (2007)

an approach separating the human worker from the process and performing the role change from a process executor to a process supervisor and guider role.

4.1.1 Traditional no-bake molding process

The traditional no-bake molding process is illustrated in Fig. 4.2 and is usually performed by a small team of skilled employees (up to 4). The process is initiated with the positioning of the molding flask and preparatory work. Depending on the type of cast part, the cast parts model consists of separate parts. Typically, a complete molding flask set consists of lower flask, upper flask, and (several) cores. After aligning molding flask and pattern, the filling and distribution of the mold material is the next step in the process procedure. Here, the mold material mixer is either manually pulled over the flask or it is remotely controlled and electrically driven to realize a rough distribution of the mold material. Following the filling path of the mold material mixer, the employee is fine-distributing the mold material with hands and feet or some auxiliary equipment to the exact pattern contour. In parallel the compression is performed that needs to be applied within a recipe-dependent time span (usually about 15 Minutes) due to the chemical reaction of the added chemicals. In Fig. 4.3, the fractography of resin-bonded mold material is illustrated. Major characteristic to this technique of mold forming is that once the bindings between the sand particles have been established, compression energy can destroy the bindings that in consequence will not be re-established. The compression is realized with basic tools such as rods, manual compactors, or more sophisticated pneumatic driven sand rammers. However, depending on the accessibility the compression is also achieved by foot-compression of the employee. Filling, distribution, and compression of the mold material is repeatedly performed as long as the molding flask is filled up. After a final compression, the surface is leveled using simple leveling rods or similar tools and the drying phase follows. The model is pulled after a couple of hours as the solidification process allows. After approximately 24hours the mold is cleaned and coated with black wash. After the mold is quality controlled, the mold is released for the casting process.

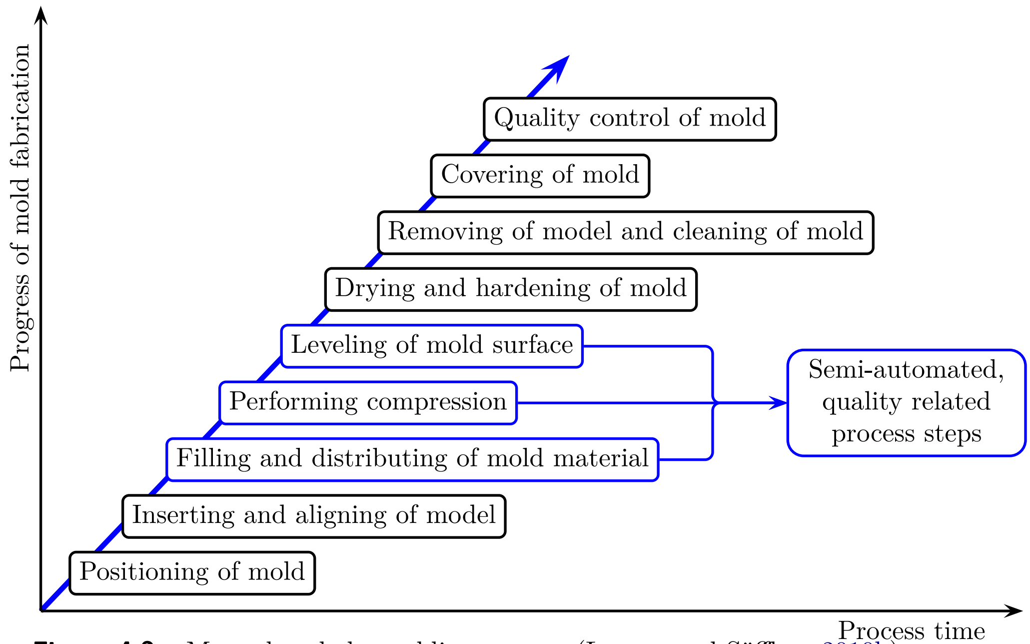


Figure 4.2 – Manual no-bake molding process (Langer and Söffker, 2010b)

Analyzing the handcrafted process, the major segments of the molding process (refer to Fig. 4.2) are identified as

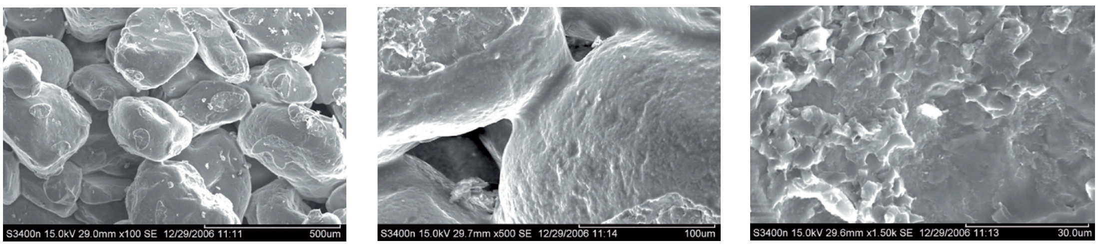
(i) distributing foundry sand in the molding flask (refer to Fig. 4.4a),

(ii) uniform compression of foundry sand layers in the molding flask by impulses (refer to Fig. 4.4b),

(iii) repeating (i) and (ii) until the molding flask is completely filled, and finally

(iv) leveling the mold surface.

However, handcrafting according to the illustrated process description and mentioned steps results in a suitable mold quality, the cast part quality is varying as the process has a low repeatability leading to varying manufacturing defects and individual rebuilding concerns. In literature and experiments the sand compression is identified as one major cause for these quality issues (refer to Söffker et al., 2013c) meaning that the mold quality is related to



(a) Binding manifesting (resolution 500μm) **(b)** Binding manifesting (resolution 100μm) **(c)** Binding manifesting (resolution 30μm)

Figure 4.3 – Fractography of no-bake mold material (Photos: Yuyan and Yingmin, 2009)

(a) Manual molding material distribution

(b) Pneumatic-driven molding material compression

Figure 4.4 – Quality related process steps of no-bake molding technique (Photos: Bundesagentur für Arbeit)

an optimal, uniform compression (determined by measured sand package stiffness) during the handcrafted process. Main challenge for automation approaches is the - up to now - unavailability on a practical solution for the in-process quality control of the achieved compression (e.g. sensor systems, Bast and Malaschkin, 2008) and a direct feedback to the human operator.

Referring to Wang (1992), automatic mold compression methods, such as

- shake and squeeze compression,
- impulse compression, and
- gas-impulse compression

have been analyzed with respect to their feasibility and occurring mold defects. Shake and squeeze compression is not applicable due to the dimension of the molding flasks. Furthermore, in some factories locally fixed cavern flasks are popular making the installation of shake and squeeze actuator complex and cost-intensive. Almost the same is true for the gas-impulse compression. As far as the results show, model defects can only be avoided (or at least reliable fore-casted), if a sufficiently high pressurization is achieved leading to cost-intensive installations. The impulse compression technique correlates to the established traditional manual molding technique and is used as blueprint for tool design of the semi-automated molding process (refer to Section 4.2.1).

4.1.2 Process analysis

Tan et al. (2008, 2009) extend classical Hierarchical task analysis (HTA) (refer to Shepherd, 1998) to consider task allocation (manual, automatic, and collaborative) in cell production. Benefits are discussed with respect to application-based requirements as total representation of operation, representation of operation collaboration for operation planning, safety development, and information support and performance evaluation. Especially, information support tends to a task-specific filtering and displaying of information to improve human operator interactions.

Applying HTA allows structuring and identifying working routines and thereby improve collaboration of human operators and automation systems (Tan et al., 2008). In the considered application of the automation of a handcrafting molding process, the HTA is performed by studying the manual manufacturing process. A small group of human workers is performing several repeated steps in order to build up a mold. The analysis leads to the superficial structure illustrated in Fig- 4.5, whereby the two tasks 'Filling mold sand' and 'Compressing mold sand' are repeatedly performed until the molding flask is completely filled. In fact, these repetitive procedures offer a certain potential of automation as these procedures are process and product quality-related and also skill-/experience-based, respectively.

In Fig. 4.5 the whole process is given in detail. Considering human factors within the given subtasks leads to necessary automation when dealing with the molding material. Thus, human worker are completely decoupled of tasks involving molding material handling. When focusing on economical goals, all mold quality related working steps need to be maintained or improved (by automation). Consequently, HTA leads to sub-processes or similar descriptive elements, such as

- tasks (Tan et al., 2012; Tan et al., 2008, 2009),
- scenarios (Robertson, 1995),
- cases (Nwiabu et al., 2012a,b), or
- scenes (Söffker, 2008)

that are defined differently, however all definitions are leading to a discrete framework with certain advantages and disadvantages as already discussed in Chapter 3.

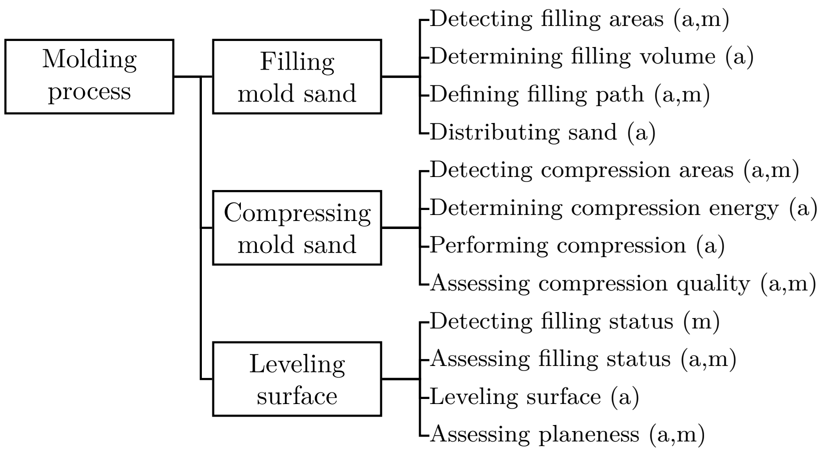


Figure 4.5 – Superficial HTA of manual no-bake molding process
(a - automated, m - manual)
(Langer and Söffker, 2011b)

The HTA is the basic description to improve the understanding of the overall process as well as to identify the undocumented skill- and knowledge of the employees. Having the relation of experience and process quality quantified in the way of task and goals within the overall process represents the input to the semi-automated realization. The process control and information-based decision support system is macroscopically based on the mapping of HTA sub-processes to the SOM action space that is used as blueprint for the implementation as illustrated in Section 3.2.1.

From the superficial HTA of the no-bake molding further analysis of the process topology is performed by applying the CTT method. According to Paternò (2000), CTT can be used to obtain an overview of the inner process structure as well as local and global dependencies.

Table 4.1 – Synthesis of optional assistance and CTT-relations (refer to Paternò, 2003)

<table>
<tr><th>Symbol</th><th>Relation</th><th>Description/Assistance</th></tr>
<tr><td>>></td><td>Enabling</td><td>Specifies second task cannot begin until first task performed.</td></tr>
<tr><td>[] >></td><td>Enabling with information passing</td><td>Specifies second task cannot be performed until first task is performed, and that information produced in first task is used as input for the second one.</td></tr>
<tr><td>||| / |[]|</td><td>Concurrent (communicating) tasks</td><td>Tasks that can exchange information while performed concurrently and in any order or overlap without any restriction.</td></tr>
<tr><td>[] / [></td><td>Choice and Disabling</td><td>Specifies two tasks enabled, then once one has started the other one is no longer enabled. The first task (usually an iterative task) is completely interrupted by the second task.</td></tr>
</table>

In Tab. 4.1, the symbol set of CTT analysis is illustrated. The symbols are representing the type of interconnection and the procedural relation of (sub-)processes within a CTT. The relations are making dependencies (causal, time, ability) transparent.

In Fig. 4.6 to Fig. 4.8 the result for both, the general process and the major sub-routines of interest as mold compaction and mold distribution are illustrated.

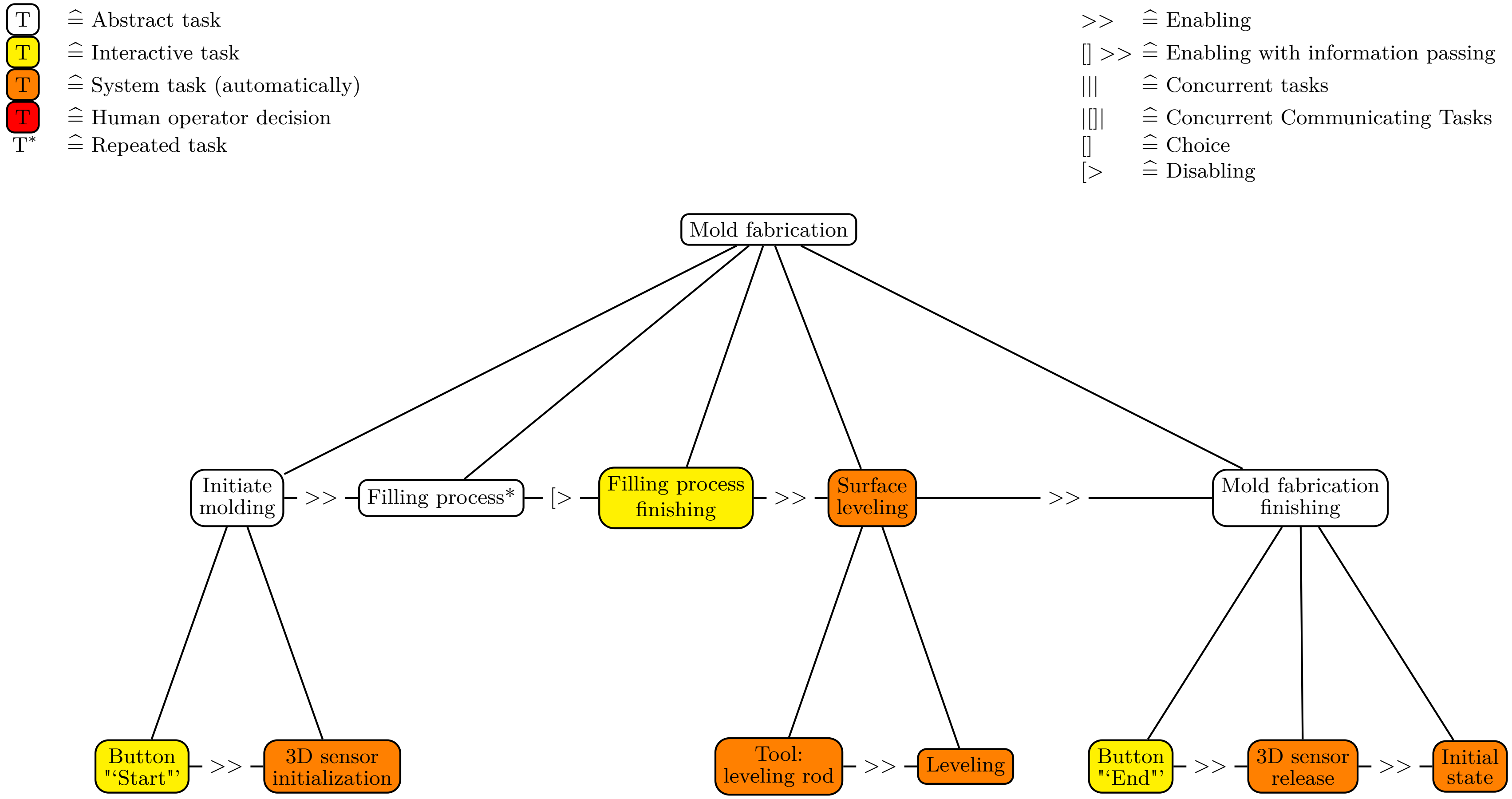


Figure 4.6 – CTT of the task “mold creation”

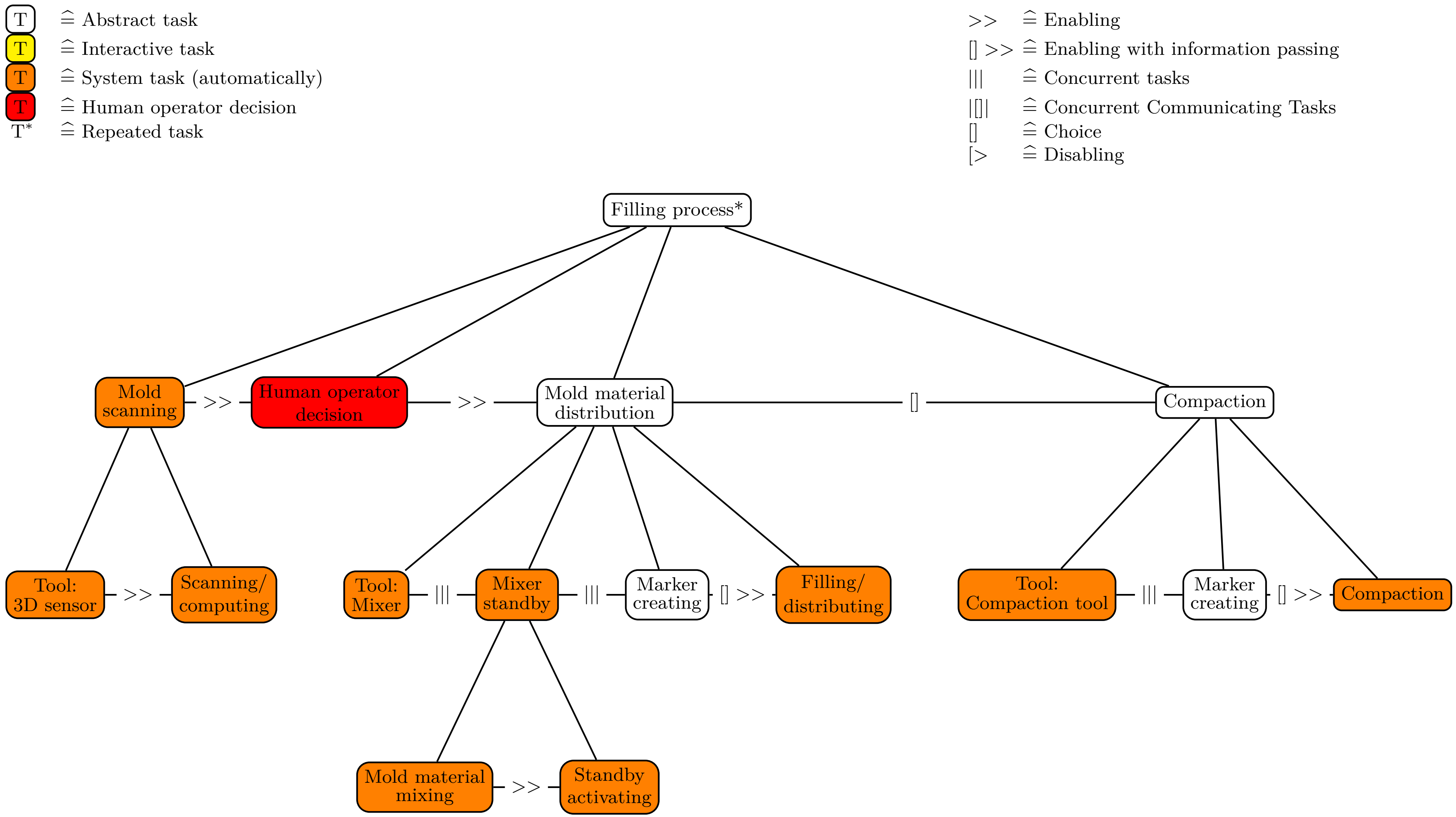


Figure 4.7 – CTT of the task “filling process”

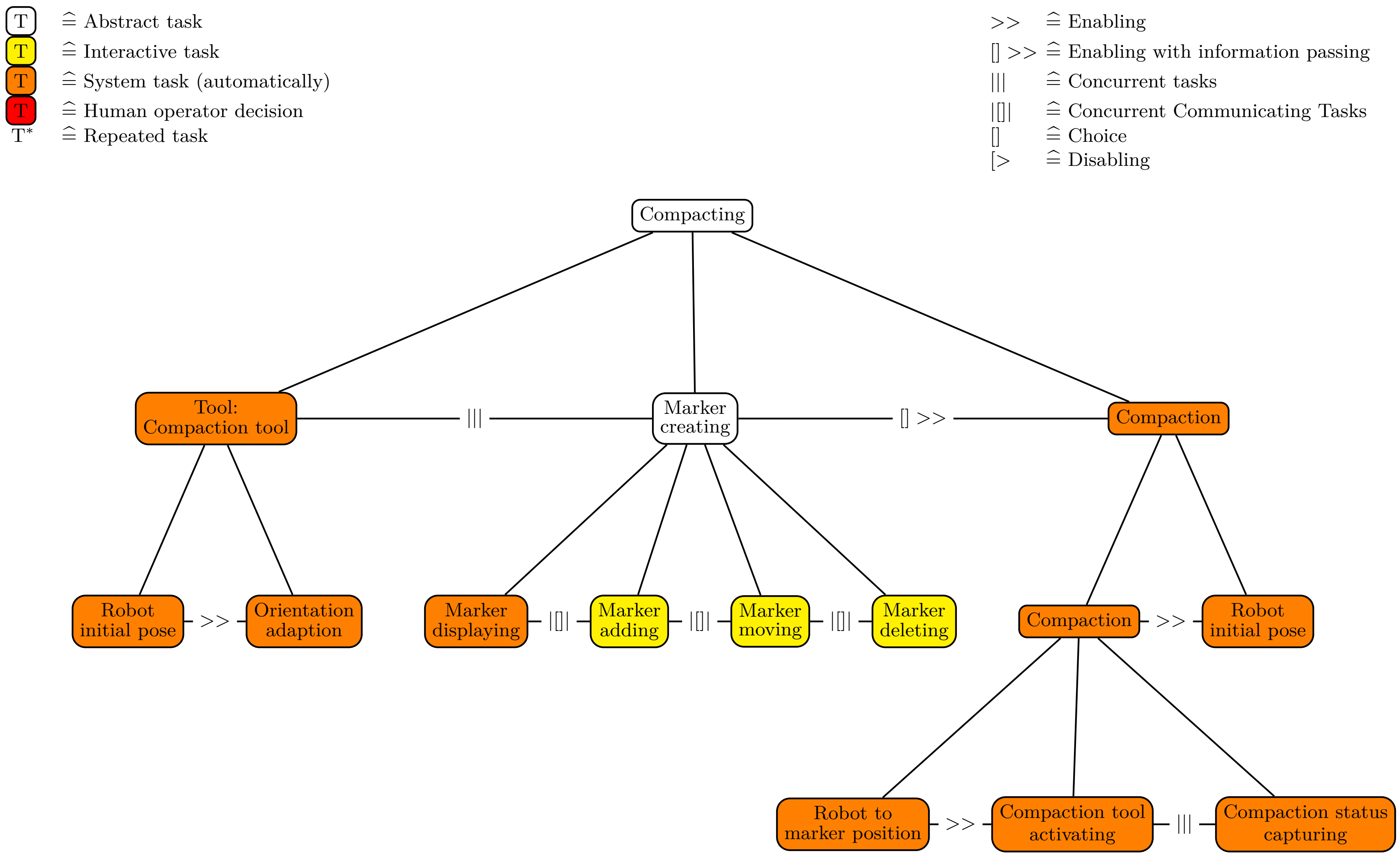


Figure 4.8 – CTT of the task “compaction”

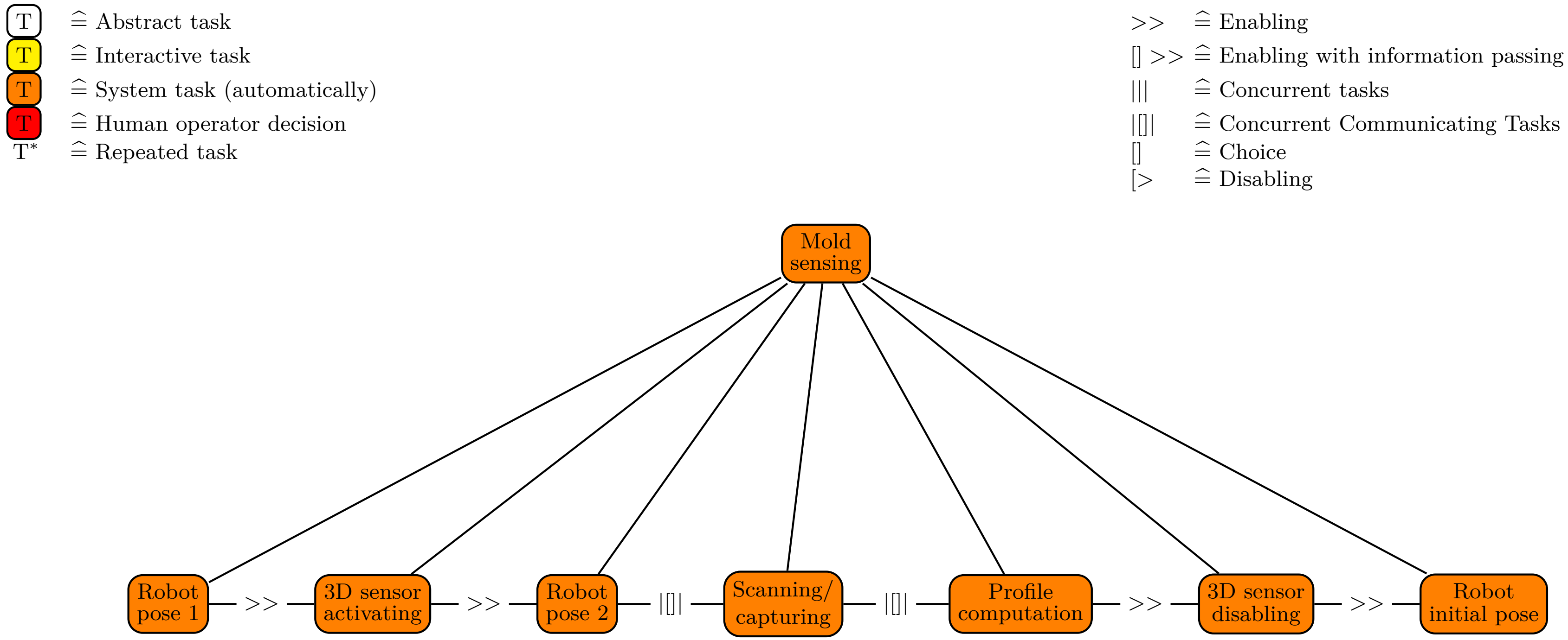


Figure 4.9 – CTT of the task "mold sensing"

4.2 Mechatronic realization of semi-automated no-bake molding

As introduced spatial separation of human operator and no-bake molding process enforces process understanding on the one hand and on the other hand an automation system that can replace human physical actions. In the following, the identified process quality variable and the Flexible manufacturing cell (FMC) are introduced.

4.2.1 Tool and process design

Impulse compaction of mold material

In literature the mathematical representation of mold material compaction is treated by several authors e.g.

- Bast and Malaschkin (2008) developed a sensor to allow in-process mold material compaction evaluation, however the solution is not practically applicable to no-bake molding process, since the sensor equipment needs to be attached to the molding flask. A fact that is not realizable within the casting industry of no-bake molds. Furthermore, the compaction information of the sensor is not representative for the entire molding flask as the achieved compaction quality is a function of the energy applied the considered volume element,
- Renker (2003) approached the problem statement by mathematical modeling the pneumatic driven compaction of mold material with and without particle transport to enhance the general performance of pneumatic compaction techniques in series manufacturing of small cast parts. The achieved results are promising with respect to machine optimization, however also not practically applicable to the no-bake technique as comparable manufacturing machines are not available for big cast parts and economically not feasible with respect to the small lot sizes, and
- Daume (1985) summarized crucial factors in the disciplines of molding material, impulse compaction, and corresponding machines. A major conclusion of the research is the inevitable necessity of compaction of the mold material in relation to the mold quality.

For this thesis, the approach consists of a flexible sensor-actuator system that allows for in-process evaluation of molding material compaction independently of the considered part manufactured. The assumption of this thesis align with those of Bekker (1969) soil-mechanical approach on terrain-vehicle systems with certain differences. The differences are analyzed with respect to available investigations of the DLR[2] as illustrated in Fig. 4.10 and Tab. 4.2.

According to the theory of Bekker (1969), that evolved from simpler models of Bernstein (1913) and Goriatchkin (1936) of the agricultural soil mechanics, Bernstein (1913) experimentally proved the fact, that if a plate penetrates soil to depth z under pressure p, then the empirical curve $p(z)$ may be fitted with

$$p = k\, z^{\frac{1}{2}}, \tag{4.1}$$

[2]German Aerospace Center – last visited October 4th, 2014

(a) Bevameter test rig of DLR soil mechanics laboratory (Photo: DLR)

(b) Molding material compaction with impact cylinder

Figure 4.10 – Comparison of bevameter test rigs of classical soil-mechanics and molding material compaction

with k denoting the modulus of inelastic deformation and $\frac{1}{2}$ the exponent of sinkage. This equation is modified by Goriatchkin (1936) to be more general to the form

$$p = k\, z^n, \quad \text{with } n \in [0, 1]. \tag{4.2}$$

Later studies found out that for both equations, Eq. 4.1 and Eq. 4.2, the k-value is sensitive to the geometric design of the plunger. Bekker (1969) improved the existing formula to consider 'cohesive' and 'frictional' effects separately. In Eq. 4.3

$$p = \left[\left(\frac{k_c}{b} \right) + k_\varphi \right] z^n, \tag{4.3}$$

k_c and k_φ represent cohesive and frictional moduli of deformation and b the smallest dimension of the contact path, e.g. the smallest edge length of a rectangular area or the diameter of a circular contact area. The parameters can be determined experimentally by bevameter tests as illustrated in Fig. 4.10.

According to the characteristics of the the molding material, which are not only influenced by humidity and granularity but also by the chemical solidification reaction of resin and catalyst, Eq. 4.1–Eq. 4.3 cannot be directly applied to molding material. Assuming $n \approx 1$ and using the known area A of the plunger, Eq. 4.3 can be rearranged to

$$\left[\left(\frac{k_c}{b} \right) + k_\varphi \right] = \frac{F}{A\, z^1}, \tag{4.4}$$

Table 4.2 – Classical bevameter test rig vs. tool design for semi-automation molding material compaction

Component	Classic bevameter	Molding material compression	Similarity score
Equipment	Hydraulic cylinder with force feedback	Pneumatic impact cylinder with force feedback and position sensor	++
Piston design	Circular or rectangular shape	Circular piston	+
Test scope	Load-sinkage relation	Load-sinkage relation as stiffness	++
Boundary condition	Not strict but determined	Varies according to the considered cast part	∘
Mechanical property	Constant	Solidifies due to chemical reaction	−−
Penetration speed	Controlled by experiment	Uncontrolled due to mechanical design of impact cylinder (only maximal contact speed is controllable by set pressure)	−

which yields an expression for the packing density of the mold material as

$$\delta = \frac{F}{z} = \left[\left(\frac{k_c}{b}\right) + k_\varphi\right] A, \tag{4.5}$$

where δ is introduced as stiffness of the compacted molding material subject to the force F and the sinkage z. Both quantities, compaction force F and sinkage z, can be captured by force-stroke measurement, when impulse compacting the molding material. Latter abilities allows for in-process feedback of compaction quality, iff the compaction quality correlates to the introduced equivalent quantity of packing density δ, which is investigated prior to completion of the FMC. The corresponding results are detailed in Section 4.2.2 and obtained with the developed compaction tool.

Tool design

Based on a priori studies (Söffker et al., 2010b; Wang, 1992), the compaction of the molding material is achieved by impact compression. The obtained results show that the final package compaction is already achieved with the initial compaction impulse. A corresponding tool design is illustrated in Fig. 4.11. The multitool consists of

- an impact cylinder that performs compaction impulses,
- a plunger that transmits compression energy to the molding material surface,
- a position and a force sensor to acquire compression equivalent process measurements,
- an adapter to hook up the mold material mixer that can be automatic driven, and
- a leveling rod to achieve the surface plainness in the final process step.

The design of the multitool satisfies the requirements of serving the FMC with a single manipulator the multitool is attached to. Furthermore, the passive mold material mixer is

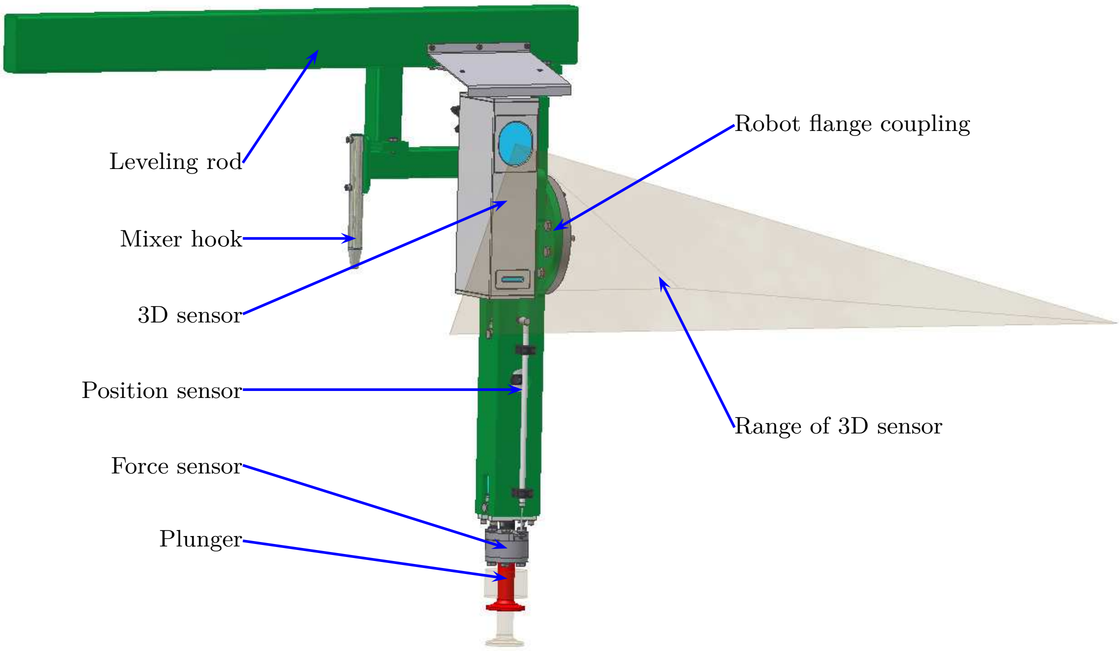


Figure 4.11 – Developed multi-tool for the flexible manufacturing cell (Drawing: Janke GmbH)

actuated by the robot as well.

The achievable potion of compaction δ is related to the impulse energy that can be applied to the mold material. The emitted impulse energy absorbed by the compacted sand package is described by Eq. 4.6. The emitted impulse energy E_{imp} with

$$E_{\text{imp}} = f\left(p, h, d, t, c_b, c_c\right) \tag{4.6}$$

is a function of the set pressure p_{set}, the filling height of the molding flask h, the initial distance of the mold material surface and the compaction surface d, the time t passed by since the solidification process is initiated, and additional chemical, geometric, or procedural dependencies. The geometric quantities are illustrated in Fig. 4.15e. Further influence factors such as

- process influences such as concentration of catalyst c_b, concentration of resin c_c, or granularity of the mold sand, and
- geometric influences, such as the plunger's geometric contact surface design or model contours,

are not explicitly covered by the performed study. The recipe has a strong effect, practically however this is a fixed setup in an industrial manufacturing process and optimized with respect to costs as the chemicals are belonging to the major cost drivers of no-bake molding.

The different correlations to achieve optimal compression parameters are illustrated in the results obtained by the performed bending bar experiment in Section 4.2.2 (refer to Fig. 4.16c to 4.16f) . The experimental time line is illustrated in Fig. 4.16d.

In order to reduce investment costs alongside with having flexibility in manufacturing, the developed multitool realizes semi-automated support to the three quality related-process

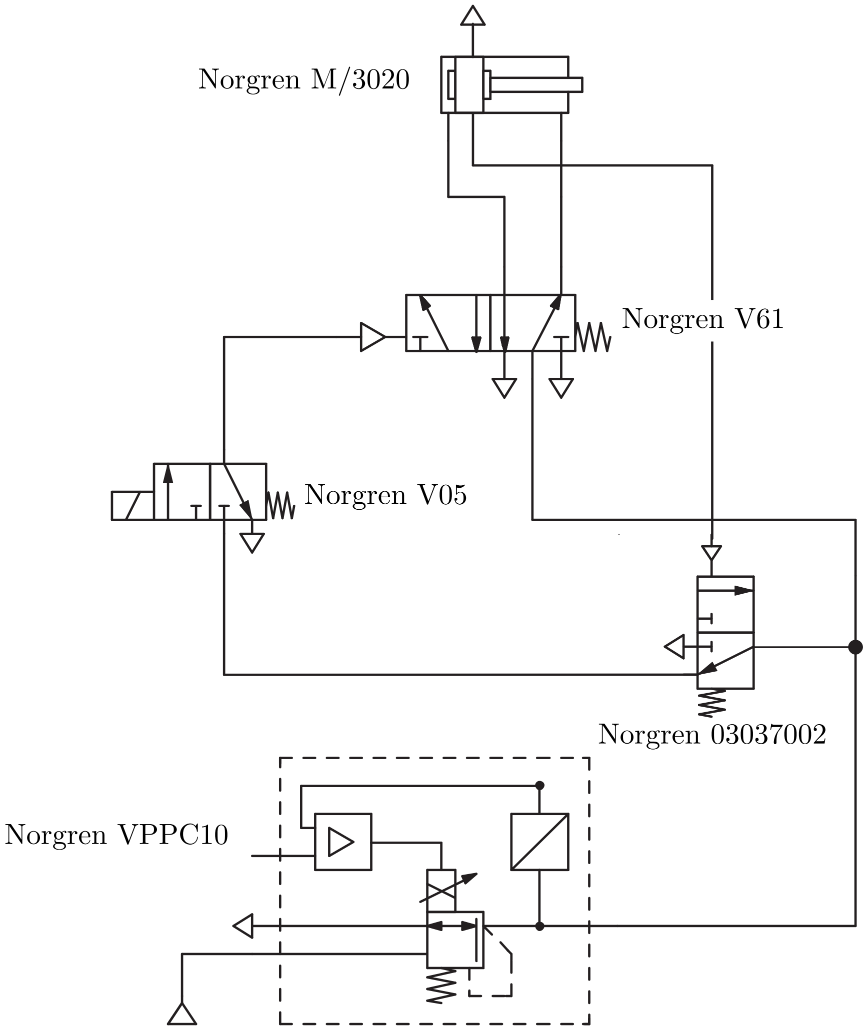


Figure 4.12 – Pneumatic control diagram (Norgren GmbH)

steps. The compaction energy is supplied by a pneumatic-driven impact cylinder and controlled mechanically by a corresponding pneumatic layout (refer to Fig. 4.12). The manipulator is positioned perpendicular to the molding material surface. The impact cylinder is prepared with the set load pressure p. The saved energy is emitted by releasing the plunger, which is then accelerated towards the molding material surface. The distance between plunger and mold material surface d is determined to be the optimal distance. The optimal distance in turn is computed by the compaction δ to be achieved and the necessary energy E_{imp} based on characteristics diagrams. According to the characteristics diagrams developed by bending bar experiments detailed in Section 4.16, the necessary energy is mapped to the equivalent set pressure p_{set} that the impact cylinder is loaded with. The compaction δ of mold material is recorded as soon as the plunger is in contact with the mold material. The deceleration curve is captured by force and position sensor and evaluated with respect to the sand package stiffness of the mold material. The (automated) assessment of the achieved sand package stiffness is feed back to the human operator.

4.2.2 Evaluation of mold quality control

Feedback of compression equivalent information to the human operator is essential in order to perform in-process quality control. Since for the no-bake molding process, no detailed information is available, experiments are necessary to formulate magnitudes of reference compression quality for widely treated molds.

Reference experiments of manual process

Common practice in molding material analysis is the evaluation of compaction stress on cylindrical probes that are created and analyzed decoupled from the factory. In a laboratory environment, molding material and cylindrical probes are prepared with the utmost achievable level of accuracy. Afterwards the compression strength of the cylindrical probes is captured by according test equipment. This procedure is intended to analyze the molding material itself not the compaction or the overall process. With this testing procedure the achievable level of compaction strength of a manual fabricated mold can be captured.

In Fig. 4.13 the experimental setup is illustrated. The drill probes are taken from a wing adapter mold of a wind turbine using a core drill. The resulting dimensions of the cylindrical probe are maintained by mechanical machining to be almost identical to a reference block as it is used within usual mold material analysis (diameter = height = 50mm). In order to analyze the compression strength of full reference blocks (refer to G_1 and G_2) as well as the compression strength distribution within the cylindrical probe, several probes were sliced (refer to C_1 to C_3 and F_1 to F_3 respectively). The prepared probes were tested with a compression-tension test equipment by the Institut für Gießereitechnik gGmbH (IfG) (Losenhauswerk). The corresponding results are illustrated in Fig. 4.14.

A significant drawback of this quality control approach is that the mold needs to be mechanically damaged in order to extract core drill probes. Hence, the mold's compression strength can be evaluated, however the mold itself cannot be further used for casting. Finally, no feedback can be given in terms of a specific compression strength with a specific spatial resolution will ensure a specific cast parts quality. Traditional reference experiments for no-bake molding are performed based on the guideline VDG, 1999. Using bending bar experiments, a qualitative evaluation of the molding material can be realized and a comparability between different institutions is given. With this procedure influences of sand quality and granularity, resin quality, recipe, and compaction can be tracked. Similar to core drill probes, testing is only applied to reference blocks that have no relation to a real mold except of the mold material used.

In order to obtain a reference for automatically compacted bending bar probes, manual fabricated bending bars were tested regarding bending rigidity and weight. The geometric dimensions of regular bending bars for mold material analysis are illustrated in Fig. 4.14a. The corresponding bending rigidity determination is performed with standard equipment (e. g. Georg Fischer). The bending bars were created by a skilled employee in handcrafting. The results of manually fabricated bending bars are illustrated in Fig. 4.14b.

Even though both test procedures,

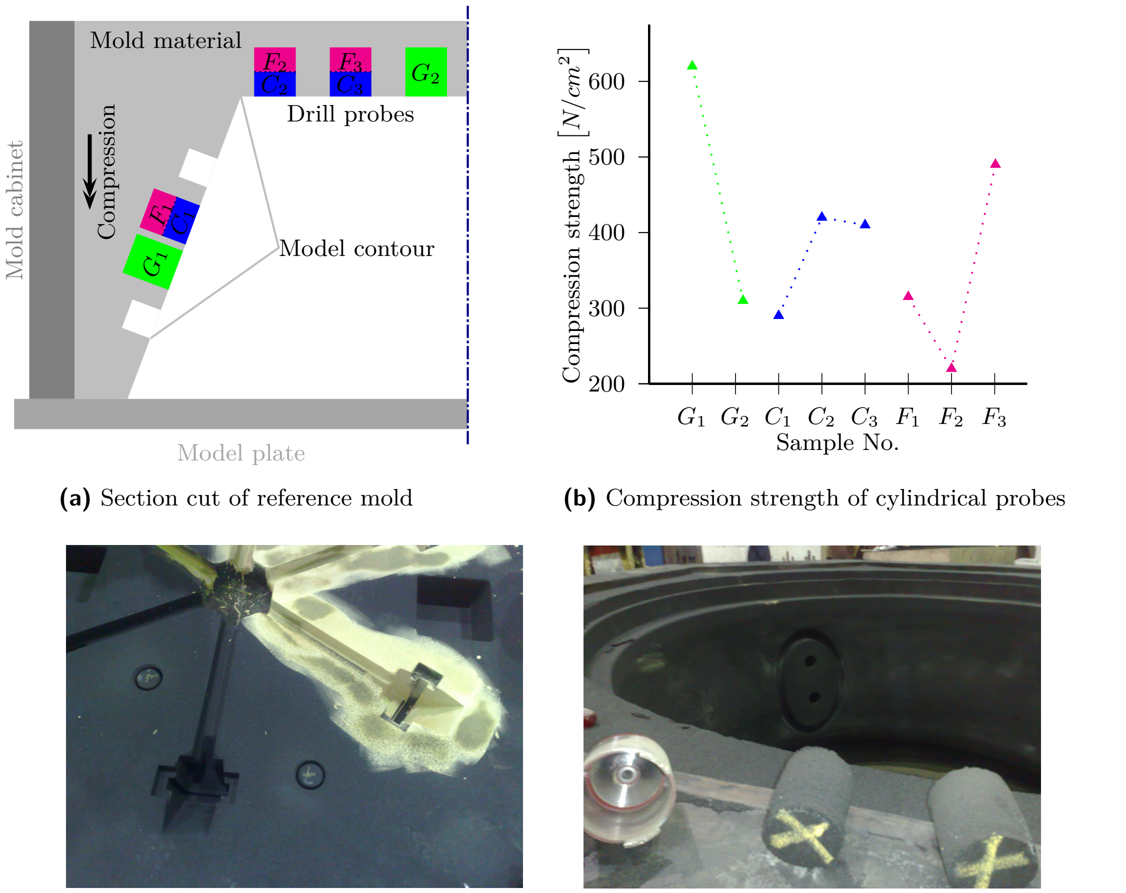
- compression strength of cylindrical probes or
- bending strength of bending bars,

are common practice in mold factories, they are not applicable to molds for in-process quality control, but the obtained results can be used to calibrate and assess the performance of the developed compaction tool.

Automated bending bar experiments

With respect to manual fabricated bending bars and the determined achievable strength, the strength of automated fabricated bending bars can be assessed. Analogously to the manual fabricated bending bars, the automated compacted bending bars are created according to the specified timeline as shown in Fig. 4.15a. An important difference is that in contrary to manual molding, compaction energy that is applied to the bending bars is exactly determined by number of impulses and corresponding load pressure. With manual molding the compaction is performed continuously while the skilled employee is in contact with the molding material. The test procedure consists of

- filling of the mold cabinet (refer to Fig. 4.15b), which is performed manually and the surface is leveled to determine the filling height h,
- compacting that is performed completely automated (refer to Fig. 4.15c). Distance to surface d and compaction sequence are predetermined according to Fig. 4.15f,



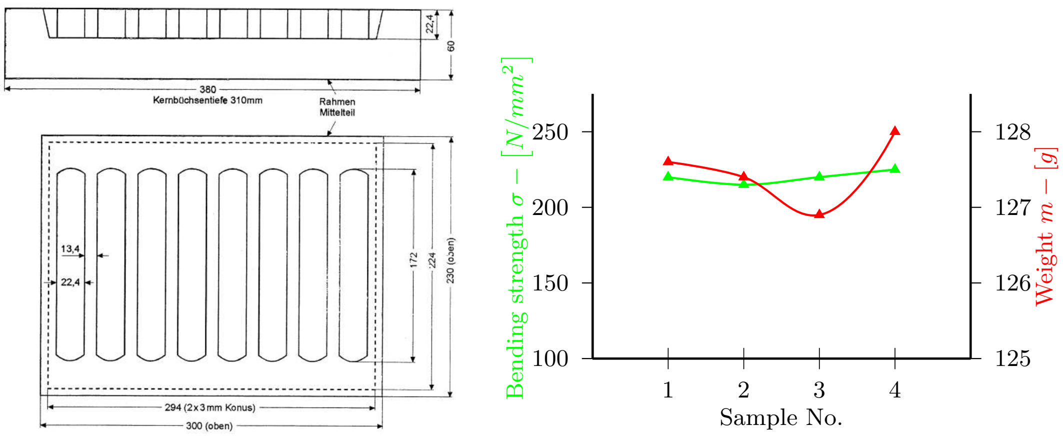
(a) Section cut of reference mold

(b) Compression strength of cylindrical probes

(c) Reference locations for drill probes (Photo: IfG)

(d) Released drill probes and core drill (Photo: IfG)

Figure 4.13 – Reference probes for manual mold fabrication



(a) Dimensions of bar probes (Photo: VDG-Sheet P 72, VDG (1999))

(b) Results of handmade samples

Figure 4.14 – Manual fabricated bending bar analysis

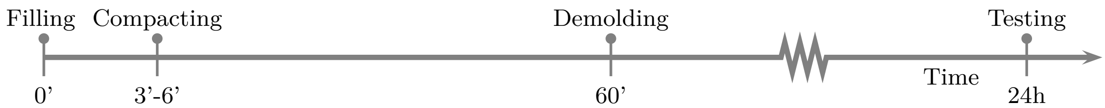
- demolding, which means extracting bending bar probes out of the mold (Fig. 4.15d), and
- testing of achieved bending rigidity with standard test equipment after a fixed drying period of about 24 hours.

The testing matrix is aligned with the assumption of Eq. 4.5 and relates load pressure p, filling height h, distance to surface d, and time t to each other to create a characteristic table for in-process adaption of applied impact. The overall parametric setup is illustrated in Fig. 4.15e.

As mentioned in Section 4.1, recipe is usually a fixed setup per factory, and thus not analyzed within the proposed experiments. However, since effects of inhomogeneous distributed resin or catalyst are affecting the result, for all experiments a reference probe is created that is not compacted at all. The reference is used to monitor irregularities in the recipe as the mold material mixer is an open-loop controlled system.

In Fig. 4.16a the emittable energy of the compaction tool is shown. A proportional relation of load pressure p and maximum velocity v is confirmed by experiment, leading to a quadratic proportional relation of load pressure p and emittable kinetic energy E_{kin}. Thereby, the major benefit of using an automated compaction mechanism lies in the gained reproducibility of applied energy. As shown in Fig. 4.16b, handmade probes repeatedly achieve a certain bending rigidity of about 210 N mm^{-2} almost comparable to the achieved bending rigidity of samples fabricated with a load pressure p of 2 bar. Significantly different is the reproducibility of the achieved bending rigidity of samples fabricated with a load pressure p of 3 bar to 4 bar. A fact that is changing again, when increasing the load pressure to the maximal applicable value of 5 bar. The fabricated, uncompacted reference probes with a determined bending rigidity of about 150 N mm^{-2} indicate that the chemical recipe is comparable over the different experiments.

Since the emittable energy can be adjusted by several variables, e.g. load pressure, also the distance to the surface is studied as illustrated in Fig. 4.16c. The setup differences are modified by the initial position of the compaction tool. A value $d = 0$ means the piston to sit on the mold material surface, whereby $d \neq 0$ is indicating an offset of the value of d. With respect to the emittable energy of the compaction tool, the parameter d is set to the

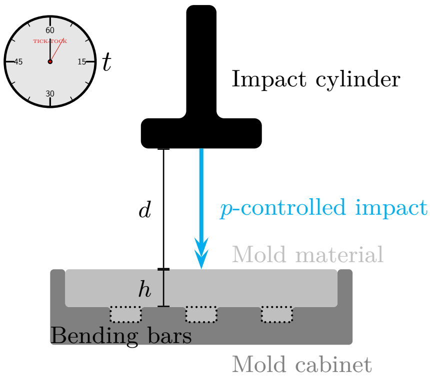


(a) Timeline of bending bar experiments

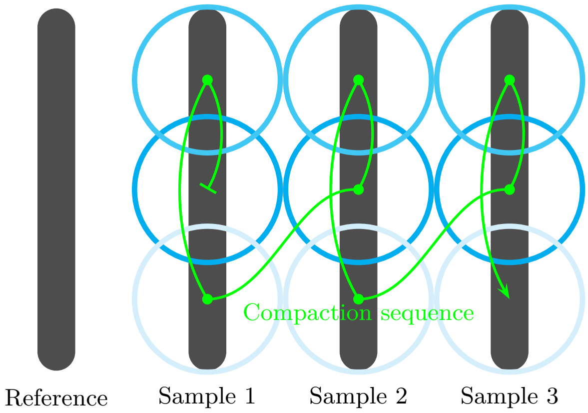
(b) Filling of mold material

(c) Impulse compaction of bending bars

(d) Resulting bending bars



(e) Parametric setup



(f) Compaction areas

Figure 4.15 – Experiment overview of semi-automated compacted bending bar experiments

Table 4.3 – Determination of optimal surface distance d

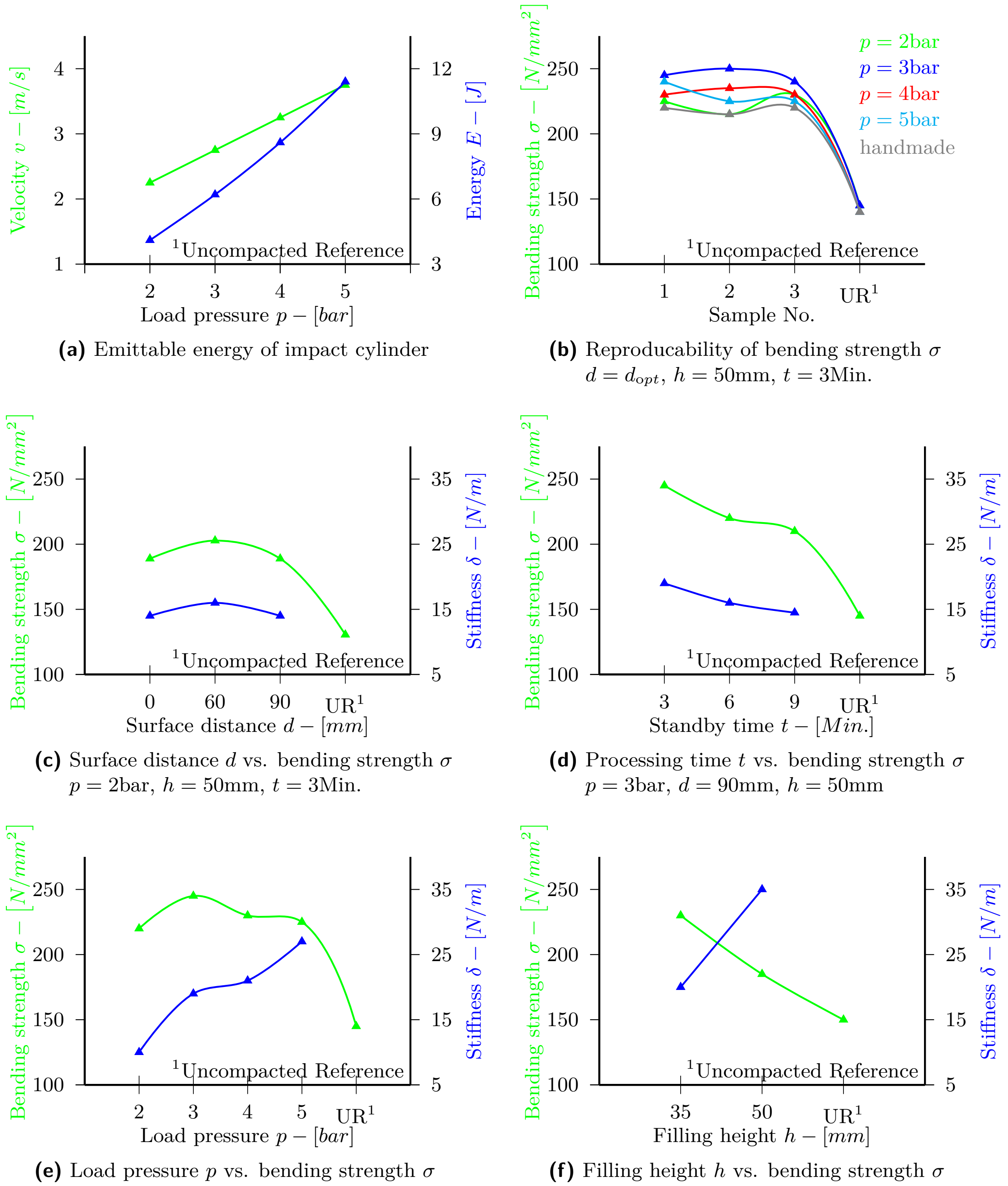
Load pressure p	**Stroke to maximal velocity**
2 bar	85 mm
3 bar	92 mm
4 bar	100 mm
5 bar	102 mm

value of reaching maximal velocity (=maximal kinetic energy) at the top plane of bending bars. The optimal distance is changing over the load pressure as collected in Tab. 4.3.

As illustrated in Fig. 4.16c, the achieved bending rigidity can be positively effected with setting the initial distance of the piston according to the stroke that is necessary to accelerate to maximal velocity before reaching the mold plane.

Since the chemical reaction of resin and catalyst is initiated when first time contact with the mold material, processing needs to satisfy certain time limits. In Fig. 4.16d, the time effect on the recipe is illustrated with respect to the bending rigidity which decreases as time is passing by.

In addition, the load pressure p can be easily applied to cover ranges of achievable bending rigidity, which is confirmed by Fig. 4.16e. A load pressure of 2 bar is equivalent to handmade



(a) Emittable energy of impact cylinder

(b) Reproducability of bending strength σ $d = d_{opt}$, $h = 50$mm, $t = 3$Min.

(c) Surface distance d vs. bending strength σ $p = 2$bar, $h = 50$mm, $t = 3$Min.

(d) Processing time t vs. bending strength σ $p = 3$bar, $d = 90$mm, $h = 50$mm

(e) Load pressure p vs. bending strength σ $d = d_{opt}$, $h = 50$mm, $t = 3$Min.

(f) Filling height h vs. bending strength σ $p = 4bar$, $d = 90$mm, $t = 3$Min.

Figure 4.16 – Sample results of semi-automated compacted bending bar experiments at room temperature (uncontrolled), quartz sand H32 (new sand), resin concentration c_b =1.02 %, catalyst concentration c_c =0.3 %

samples as mentioned before and illustrated in Fig. 4.14. In the limits of 3 bar to 4 bar, the emitted energy leads to a comparably advanced bending rigidity, and when increasing to 5 bar the achieved bending rigidity decreases again.

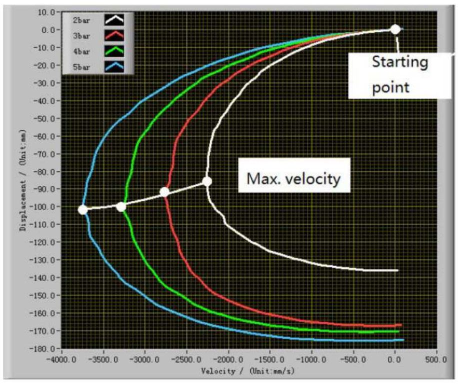
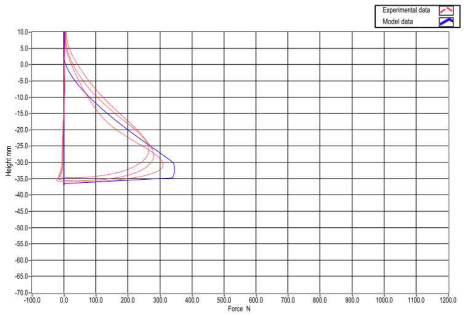
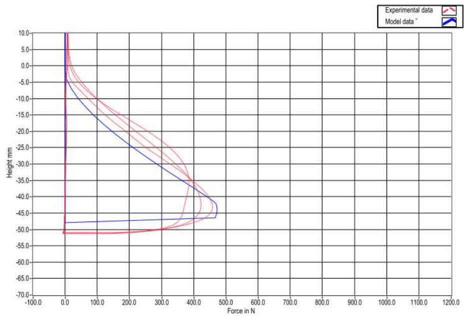


Figure 4.17 – Correlation of displacement and velocity of compaction tool



(a) Verification of mold material model – $p = 2\,\mathrm{bar}$



(b) Verification of mold material model – $p = 3\,\mathrm{bar}$

Figure 4.18 – Model verification of impact compression

For the application certain filling heights need to be considered. In Fig. 4.16f the effect of filling height is initially evaluated. With increasing filling height and thus increase of compaction layer thickness, the achievable bending rigidity reduces when considering a constant load pressure.

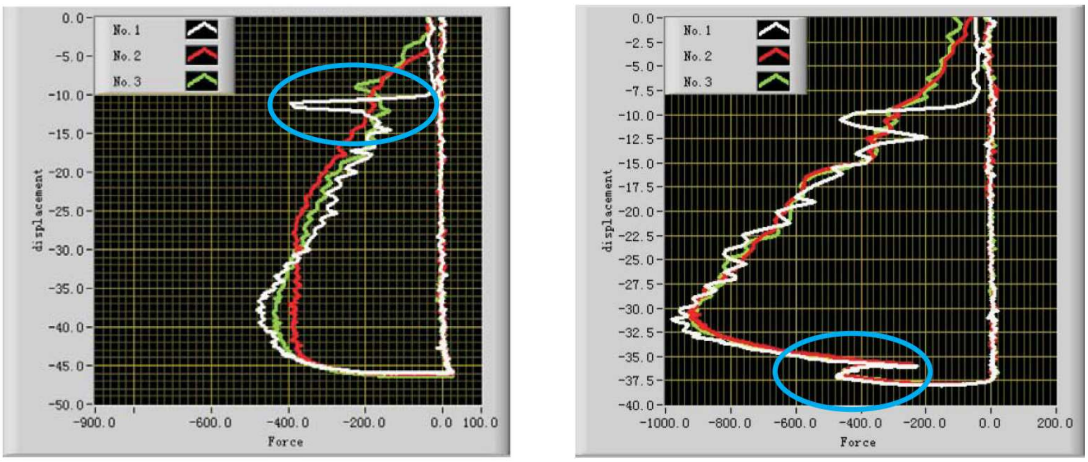
Summarizing the performed bending bar experiments, the developed tool is capable to apply reproducible impact compaction to the mold material, whose impulse energy can be adjusted by the geometric distance to the mold material surface d and load pressure p according to the locally determined filling height.

Model verification and effects of impulse compaction

As introduced in Eq. 4.6 is a function of various parameters that are verified by the performed experiments. In order to verify that the Bekker's approach is valid when dealing with mold material instead of soil, the principal behavior of mold material is investigated by theoretical modeling and verified with the same set of experimental data. Detailed information on the model can be retrieved in Zhong (2012).

In Fig. 4.18, two samples of the performed model verification are illustrated. The proposed theory of Bekker (1969) can be used to describe qualitatively the behavior of the mold material compression. Besides, two effects were identified that are connected to the decreasing bending rigidity e.g. when setting the load pressure to its maximum,

- surface tension on leveled surfaces (Fig. 4.19a) and



(a) Surface tension effect

(b) Shockwave effect

Figure 4.19 – Effects of impact compaction

- shockwave reflection on pattern plate (Fig. 4.19b).

The chemical reaction of resin and catalyst is advanced at the boundary layer. Hence, the bindings are evolving from the boundary layer towards the inner volume of the mold. The resulting surface tension leads to an advanced force in order to break through, which is indicated by the experimental data in Fig. 4.19a.

The shockwave effect occurs if the ratio of load pressure p and filling height h is over a certain limit. In this case the sand layer is not capable to absorb the entire emitted energy and thus, the remaining potion is reflected at the pattern plate. The reflected energy impulse is reducing the package stiffness according to the retrieved experimental results.

With the gained knowledge of how to adjust the emittable impact energy of the developed tool under the given (measured) cabinet conditions and in doing this, the achievable bending rigidity, the corresponding compaction process can be designed and integrated into the overall process in the FMC.

4.3 Developed semi-automated manufacturing cell

4.3.1 Outline of the flexible manufacturing cell

The underlying research is subject to a real flexible manufacturing cell for no-bake molding. The principle design as draft of the manufacturing cell is illustrated in Fig. 4.20 and its realization in Fig. 4.21. The overall FMC consists of several mechanical engineered parts, such as

- industry robot (Type: Fanuc M900iA-350 with control unit R-J3iB),
- mold material mixer (Type: AAGM 5-10 tons/hour),
- universal manufacturing tool (also referred to as multitool, Fig. 4.11) including
  - impact cylinder (Type: Norgren M/3020M),
  - 3D sensor (Type: SICK Ruler E 1200),

  - force sensor (Type: HBM U10M),
  - position sensor (Type: HBM WA300),
  - mold material coupling,
  - leveling rod, and
  - several pneumatics equipment (refer to Fig. 4.12),
- molding flask with model,
- mixer's docking gibbet, and
- mold material feed cabinet

as well as a variety of auxiliaries, e.g. chemical pumps, compressed air supply, etc. The realized demonstrator is capable of producing molds up to the dimension of $2500 \times 1800 \times 800$mm. The reference model is representing halve of a valve for turbo machinery. The feasible physical dimensions of the molds are majorly limited by the reachability the industry robot.

4.3.2 Control layout of the flexible manufacturing cell

The corresponding control scheme for the manufacturing cell is illustrated in Fig. 4.22.

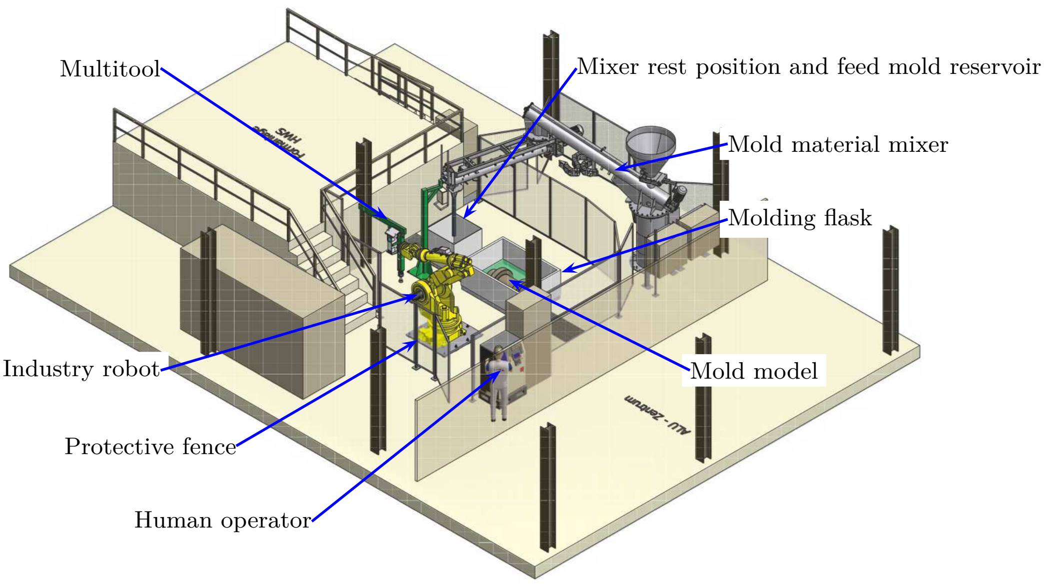
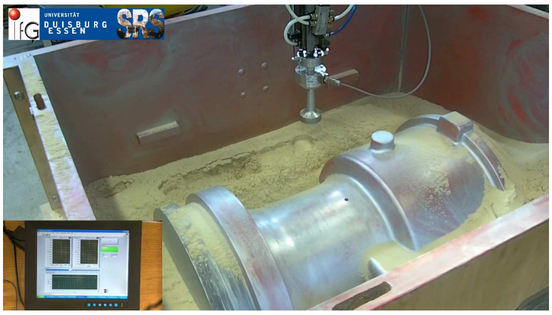


Figure 4.20 – Flexible manufacturing cell (Drawing: Janke GmbH)

The Process control and visualization system (PCVS) is the central element of the FMC as point of concentration of information and output of control signals for all actuators within the FMC. For the large equipment such as the mold material mixer and the industry robot, the PCVS provides control signals to the interfaces to the corresponding individual control units. The detailed control of the individual equipment is realized by the proprietary logic and implemented control algorithms of their individual controllers. The physical connection of the equipment to the PCVS is provided by

(a) Scene capturing with 3D sensor

(b) Human operator induced automated molding flask filling



(c) Mold material compression with the developed impact actuator

(d) Fully automated molding flask surface leveling

Figure 4.21 – Realization of the flexible manufacturing cell demonstrator for semi-automated no-bake molding (Langer and Söffker, 2012c)

- PROFIBUS – industry robot,
- digital I/O (DI/DO) – mold material mixer, compaction tool, 3D-sensor trigger,
- GBit-Ethernet over TCP/IP – 3D-sensor,
- analog I/O (AI/AO) – compaction impulse control, force-/stroke measurement of compaction tool, and
- FIREWIRE – real-time camera[3],

whose information are fused by the PCVS or provided by the PCVS, respectively. The PCVS itself consists of a real-time controller with including

- the control unit
  - NI PXI-1042Q Quiet 8-Slot Chassis,
  - NI PXI-8106 Core 2 Duo 2.16 GHz Controller,
  - NI PXI-8231 GBit Ethernet Controller
  - 2×NI PXI-6220/1 M Series DAQ,
  - PXI PROFIBUS Master/Slave Interface,
  - FPT-1015 15” Flat Panel Touch Screen with VGA Interface, and
- the signal processing unit

[3]Real-time video surveillance is intended to be available with the FMC, however is only used for maintenance and setup process not for process assistance

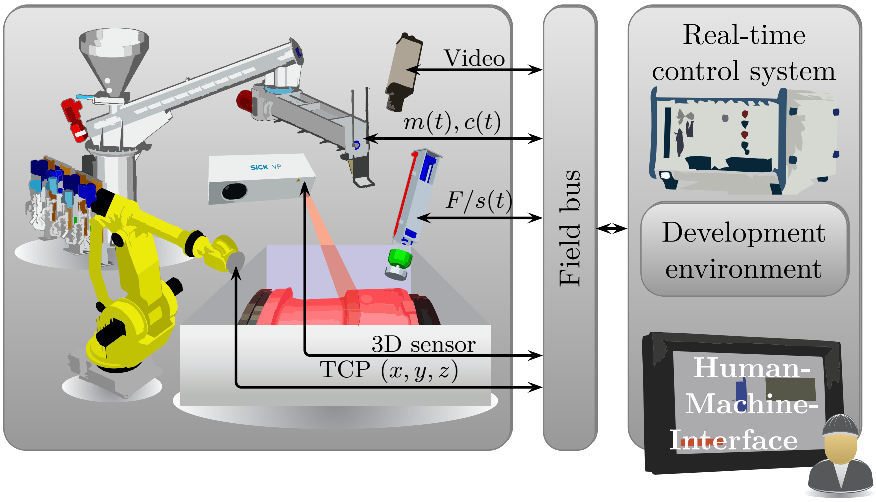


Figure 4.22 – Process control scheme of FMC including PCVS (Langer and Söffker, 2010b)

- 2×HBM 1-ML55B measurement amplifier,
- HBM 1-CP42 communication unit, and
- 2×HBM 1-AP01l interface cards

with the corresponding software kits.

In combination of the analyzed process topology for manual manufacturing as illustrated in Fig. 4.2, the developed FMC and the including the multitool as central instrument for replacing physical work, a corresponding modular process control algorithm is proposed.

4.4 Operator guidance and supervision assistance implementation

According to the introduced process topology, human operator's strength are taken into consideration by allowing both flexibility of correcting machines algorithmic results and align with a subjective understanding, however process quantified process control variables are set non-adaptable and aligned with measurement data. The overall process guiding and supervision is realized based on the SOM-model introduced in Section 3.2.1 and transferred to statecharts. Statecharts algorithm are natively support by the considered hard- and software environment of the PCVS.

The general discipline of operator guidance and supervision is concentrated on three basic columns

- how to integrate human know-how of no-bake molding
  that is not documented and even complex to describe,
- how to integrate (or automate) human skills
  as characteristic unique feature of no-bake molding, and
- how to allow for an intuitive integration of human interaction
  with the newly developed FMC

to be addressed by formal approaches.

4.4.1 Process control and visualization system (PCVS)

Central component of the PCVS is the touch panel-based HMI that allows the spatially separation of human worker and FMC. The process guidance and assistance is realized by adding supporting functions to the overall algorithmic framework that itself is based on a state architecture according to SOM or statecharts, respectively.

The algorithm overview is shown in Fig. 4.23 that is primarily providing tools according to the different process steps. The algorithm is designed modular aligned to the different process stages and the corresponding requirements (such as tools, sensors, etc.). The beneficial side-effect of the modular design constitutes when designing assistance functionalities, which can be addressed to single modules, to a chain of modules, or even to the overall algorithm.

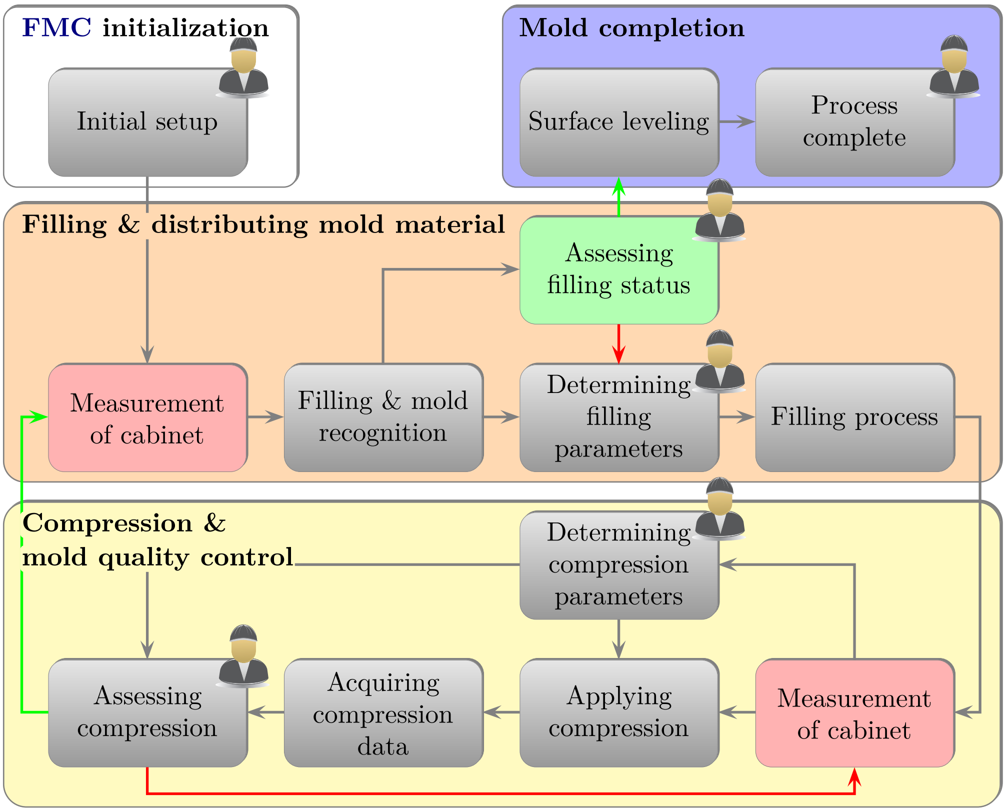


Figure 4.23 – Algorithm of realized automated human-centered no-bake molding process and highlighted steps of human intervention (Langer and Söffker, 2014)

Central interest in designing process assistance to the human operator lies in mold-quality related process steps, such as filling, distributing, and compacting the mold material. The semi-automated mold manufacturing algorithm is separated into four overall tasks to be performed

- initializing the FMC,
- filling and distributing mold material,
- compaction and in-process mold quality control, and
- leveling and finishing the mold manufacturing

that address the introduced issues of incorporating human process knowledge and assisting process guidance. The FMC initialization module includes a system-wide initialization of auxiliaries and feedback of the large equipment to the PCVS. If all the system are put into standby and the mold manufacturing can be started with the second module 'Filling & distributing mold material'.

Description of the general algorithm

The first routine measurement of cabinet is triggering the robot to change the tool to 3D-sensor and to move to the initial measurement edge of the flask. If the position is reached and confirmed by the robot control unit, the measurement of the cabinet is performed by moving the 3D-sensor along the cabinet and grabbing cross section profiles that are rendered to a volume model in real world coordinates (the origin of all position measurement is the industry robots base). The resulting volume model is output to the next routine, which is optimized with respect to rendering efforts (Langer, 2011).

The routine 'filling and mold recognition' provides general information of the flask's status as the edges and the filling level that is forwarded in parallel to an assessment and to the routine of filling parameter determination. The filling status assessment is performed in order to detect whether the molding flask is completely filled or not by the routine 'assessing filling status'. If not, the filling characteristics are determined by using several subroutines

1. to determine the edges of the molding flask
   (unnecessary if the flasks position is fixed, e.g. cavern flasks),
2. to determine the overall necessary volume and adapt the target filling height,
3. to partition the volume of the flask,
4. to calculate the required filling volume per segment,
5. to optimize the filling path in order to reduce accelerations and preserve the equipment, and
6. to output the filling path and corresponding velocity profile

by the routine 'determining filling parameters', which is further detailed in Section 4.4.1.

Having tuples of positions and velocity, the filling process can be performed by providing both to the robot's control unit that is handshaking with the PCVS. The tool change to the mixer is performed and the mixer is set to conveying feeding sand. In parallel the robot is docking the mixer. After human operator's confirmation, the filling process is executed and an uncompacted sand layer is added to the molding flask.

Another Measurement of cabinet is performed for the open-loop filling process and forwarded to routines of determining compression parameters and applying compression. According to the history of scans, areas with new layered molding material are indicated and according to the characteristic diagrams illustrated in Fig. 4.15e, tuples of position and compaction energy are determined.

Having tuples of positions and compaction energies, the applying compressions can be performed by providing both to the robot's control unit that is handshaking with the PCVS. The tool change to the compaction tool is performed and the compaction tool is loaded with the standby pressure to reduce loading times. After human operator's confirmation of compaction locations, the compaction process is executed and the routine acquiring compression data becomes active.

The acquired compression data is evaluated with respect to the achieved compaction and compared to the set-compaction in the assessing compression routine. In case the achieved compression is less than the planned on some locations, these set will be additionally compacted upon the human operator's decision. If the achieved compaction satisfies the planned compaction parameters, the third module 'Compression & mold quality control' is finished and another measurement of cabinet is executed.

In case the molding flask is completely filled, the FMC status enters the module 'Leveling & finishing mold'. The routine surface leveling is activating the tool change to the leveling rod and is setting the robot to the molding flasks edge. Afterward the surface of the flask is peeled off dispensable molding material (in an ideal case only a marginally amount), and after another measurement of the surface's planeness, the semi-automated mold manufacturing algorithm is finished and all considered systems will rest in standby position. The implemented programmatic realization of the proposed algorithm is illustrated in Section 4.4.2

Determining filling parameters

The robot control unit expects an array of tuples T_f including position and velocity information for performing the filling path. The interface allows for forwarding the ith tuple of the form

$$T_{\mathrm{f,i}} = \langle x, y, z = z_{fix}, v \rangle_{\mathrm{f,i}} \tag{4.7}$$

to the robot's control unit that itself is interpolating a planar movement through the series of tuples in order to prevent the large equipment to cause any damage[4]. The movement is realized with a fixed z-coordinate that is the moving plane of the old material mixer. The tuples are determined based on volume segments that are created and evaluated after surface sensing. The path through the discrete volume segments is determined based on a machine-optimized KRUSKAL'S algorithm (refer to Cheilakos, 2006). The idea of the graph theory algorithm is to find a minimum spanning tree for a connected undirected weighted graph with the constraint of minimizing the acceleration changes (or jerk as derivative of the acceleration) throughout the filling phase. Details on available and developed algorithms for this application can be found in Wolff (2012).

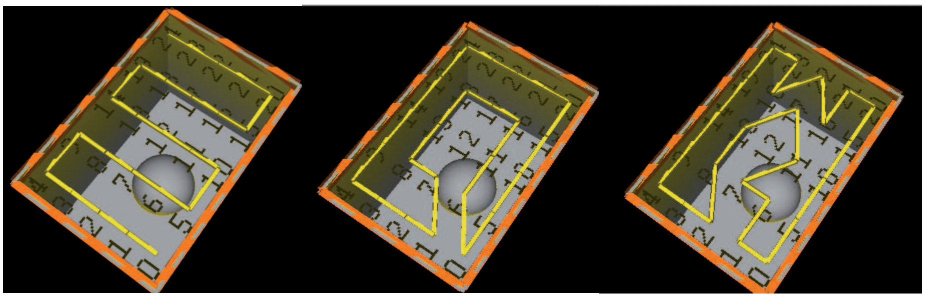
A sample result that considers a sphere pattern in the molding flask is illustrated in Fig. 4.24. The approach allows to reduce the maximum jerk on the industry robot about 25 % (refer to Fig. 4.24b), that is leading to reduced physical load on the equipment.

An optimized filling path visualization is illustrated in Fig. 4.25.

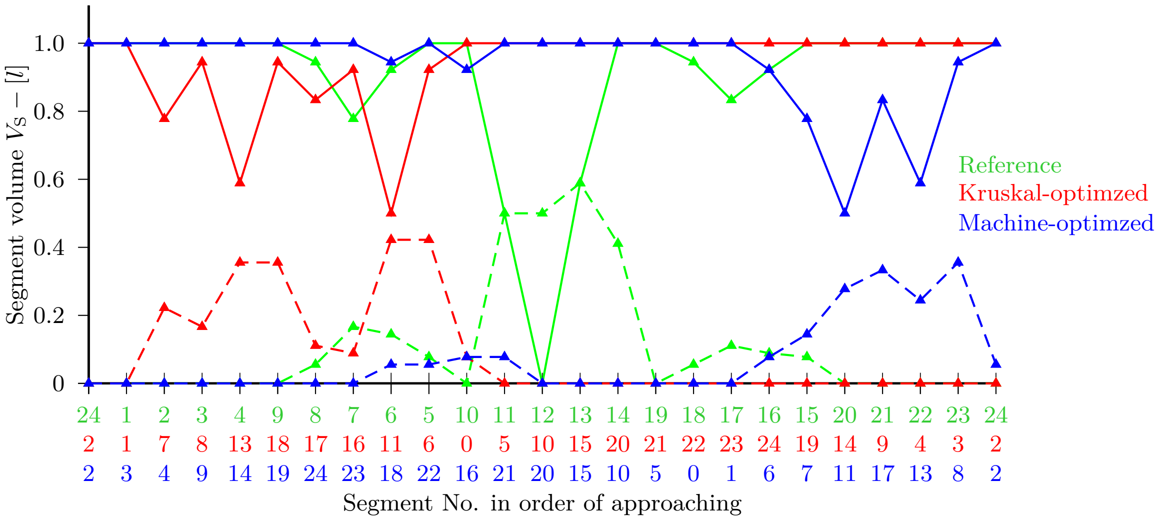
Determining compaction parameters

The robot control unit expects an array of tuples T_c including position and load pressure for performing the local compaction. The interface allows for forwarding the ith tuple of

[4] This is especially important due to the moment of inertia of the mold material mixer



(a) Optimized filling path (from left to right: reference, Kruskal-optimzed, machine-optimized)



(b) Corresponding velocity (solid) and acceleration (dashed) profile

Figure 4.24 – Result of the optimized filling path algorithm

the form

$$T_{\mathrm{c,i}} = \langle x, y, z, p \rangle_{\mathrm{c,i}} \tag{4.8}$$

to the robot's control unit that itself is interpolating a linear movement to the tuple's position. The planar position (x, y) is provided (or supervised, respectively) by the human operator, the z coordinate and set pressure p are both determined based on the characteristic diagrams based on the bending bar study in Section 4.2.2 with the constraint of minimizing p to increase the impact frequency and to speed up the compression phase throughout the process.

4.4.2 Integrative approach of human and machine control

As introduced the FMC is spatially separating the skilled human worker from the physical process, which is satisfaction of human factors due to the noxious environment of fine dust and chemicals. According to the triangle of automation (refer to 2.8), the human operator is still a key element within the HAS and majorly subject to

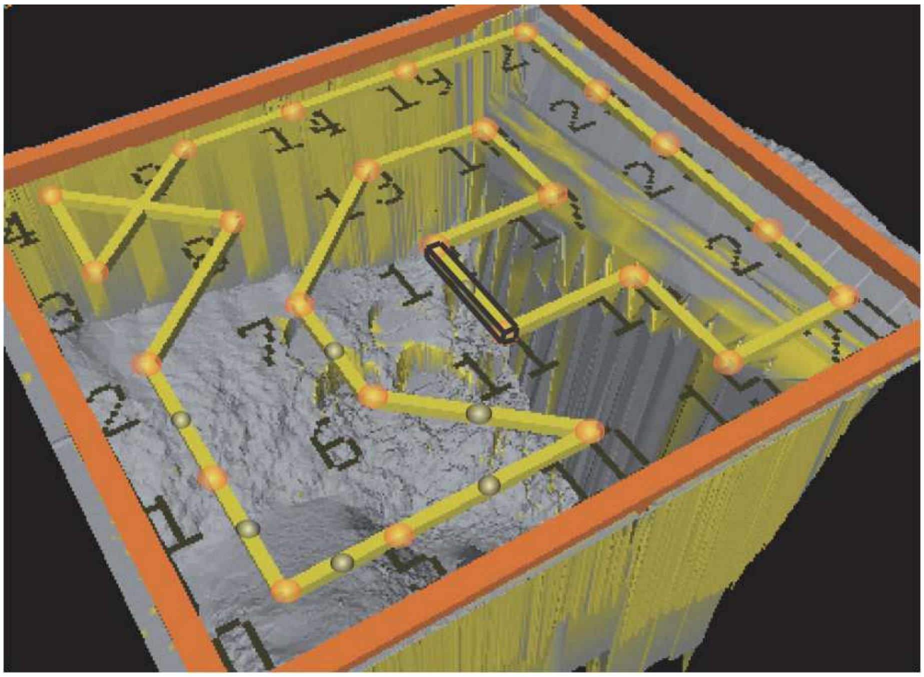


Figure 4.25 – Application of machine-optimized path computation to real mold measurement

- sense mapping and
- role substitution

while being integrated into the semi-automated process. Integrative human and machine control is related to the role substitution, however partially also to sense mapping as the assessment of 'sensed' information in most cases is the base of consecutive decision.

The integration of individual know-how of the operator is mapped to changing set data of input parameters whereas manual molding skills are mapped to operating features of the FMC. In consequence, the domain of input to provide is restricted by the amount of mapped features from the manual to the semi-automated process. From the analysis of the manual process in Section 4.1.2, the basic process steps that are directly affecting the process success are distributing and compacting the mold material. Within the task of "Distributing the mold material", the human operator knows (from experience) filling location, filling order, and filling height, which are related to the cast part the mold is intended for. Hence, integration of human operator experience in this process step means, giving the human operator the ability of providing tuples of locations and volumes within the molding flask system.

According to the process step of "Impulse compacting" the mold material, human operator sense mapping to representative magnitudes of compression qualities is an essentials and necessary step. Additionally, determining the compacting locations in relation to assessing the compaction quality is an experience-based human operator action. Hence, integration of human operator experience in this process step means, giving the human operator the ability of providing tuples of locations, set compacting parameters within the molding flask system, and allow for assessment of achieved compression.

Both, integrating human operator in FMC actions of distributing and compacting the mold material defines requirements to the HMI. These requirements are satisfied by applying

HCA-design approaches as introduced in Section 2.3 in parallel to restrictions from the application and the environment as illustrated in Fig. 2.8. The HMI-platform is a touch panel as direct input device.

As introduced in Section 3, interfaces are intended for data exchange. Data exchange in this context is covering skills and experiences, whereby skills need pre-processing in order to be available to the FMC. In Fig. B.1 in Appendix B the introduced integrative approach and its programmatic realization is illustrated. The SOM-framework as introduced in Section 3.2.1 offers the definition of characteristics originating from different domains. Hence, the representation of process variables, status variables, control sets, feedback sets, etc. are collected to a single SOM-vector. Sub-situations are set up by the human operator directly (e.g. compression tuples or distribution path tuples – refer to Section 4.4.4) and attached to the situation vector. This activity (providing individual process knowledge) can be seen as designing an ideal target situation that is provided to the PCVS which is managing corresponding actions within the FMC. While executing corresponding actions the feedback of achievement status is collected by the sensors and visualized by the PCVS that is available to the human operator for assessment (situation-based visual assistance). Additionally, the post-processing of feedback information is analyzed with respect to the underlying process and a preferred action (from the optimal process view) is offered to the human operator. However, the human operator is still the major instance of process decisions.

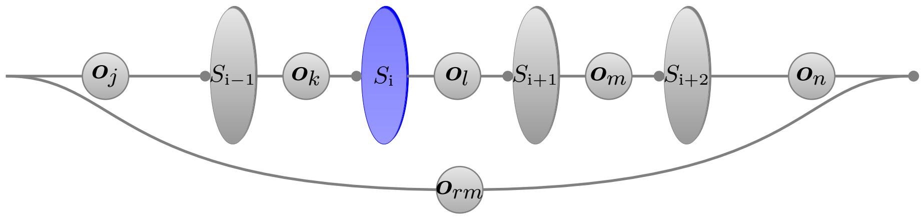
The basic instruments to keep the separated human operator integrated into the HAS is performed by the formal model (refer to Section 4.4.1) and corresponding HMI-framework design. In Fig. 4.28 the developed human guidance assistance concept is illustrated in combination with the human controller metaphor. The human operator is defining the target situation S_{des} of the FMC via the HMI. The target situation consists of several process-related information such as set of compression or distribution tuples, the process-step to perform, etc. As soon as all characteristics have been collected by the corresponding inputs or the preset of the assistance configuration, the human operator can forward the target situation S_{des} to the PCVS. The PCVS itself translates the target situation into several actions or action sequences (e.g. repetitive actions of tool exchange as illustrated in Fig. 4.26) of the FMC and initiates the execution. The resulting (or achieved) situation is feedback by the FMC as S_{meas}, which is in turn translated by the PCVS to a corresponding HMI set.

The requirement that the automation approach as introduced in this work is not perfectly governed still holds. This is explicitly necessary to consider with respect to the human operator duties, which are changed however single process steps still need to be monitored by skilled employees with an optimal process guiding support.

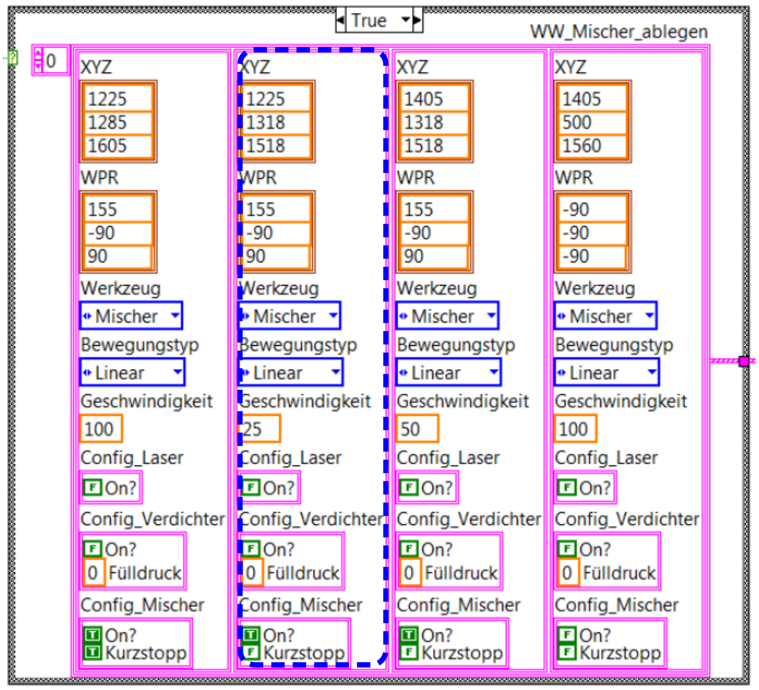
4.4.3 Implemented framework based on statecharts

The introduced action space (refer to Fig. 3.3) is an SOM-based approach. For implementation, the event-discrete representation is ported to statecharts (Harel, 1987b). In Fig. 4.27 the outline of the statecharts framework is illustrated. A detailed representation is illustrated in Appendix A.

The proposed statechart framework is a complete representation of the algorithm in Fig. 4.23. Technically, the statechart framework is mapping the state variables to real hardware interfaces to interact with the corresponding auxiliaries. The overall application that is developed to control the FMC is shown in Fig. B.1.



(a) Situation sequence of the underlying SOM process model



(b) Cluster-representation of SOM-characteristics within NI LabView (refer to Fig. 3.2)

Figure 4.26 – Situation sample of meta-operator "releasing mixer" (o_{rm}) with highlighted intermediate situation

The application consists of an initialization, three loops, and a finalizing construct. The initialization is setting up the hardware connections, such as industry robot and tool communication or 3D sensor connection. The loops are realizing

- emergency stop supervision,
- interaction with human operator, and
- physical implementation of input to the FMC

as illustrated in Fig. B.1. The finalizing construct will release allocated memory and will also close all open connections. The functionality of the developed control application is detailed in Appendix A.

The control and interaction concept is illustrated in Fig. 4.28. The HAS topology is shown in Fig. 4.28a and the corresponding interaction concept is detailed in Fig. 4.28b.

The user interaction/event generation is established by an event-environment, capturing and triggering user interactions to corresponding interface events. The collection of all

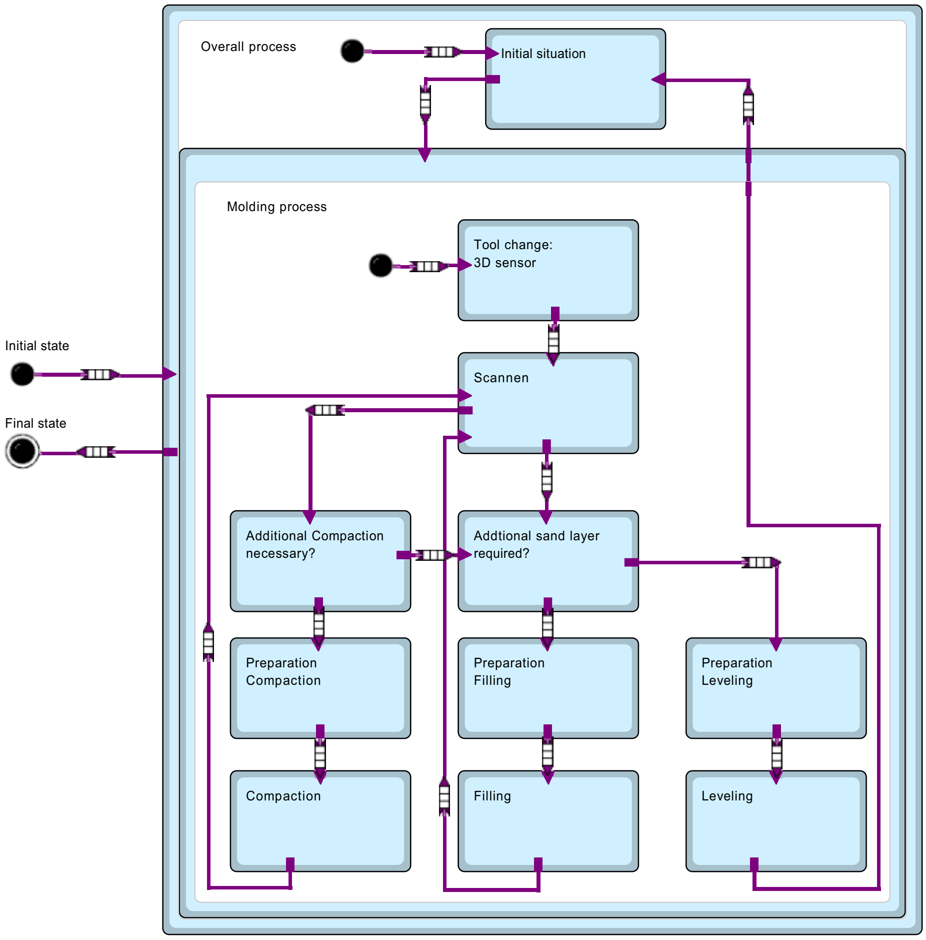


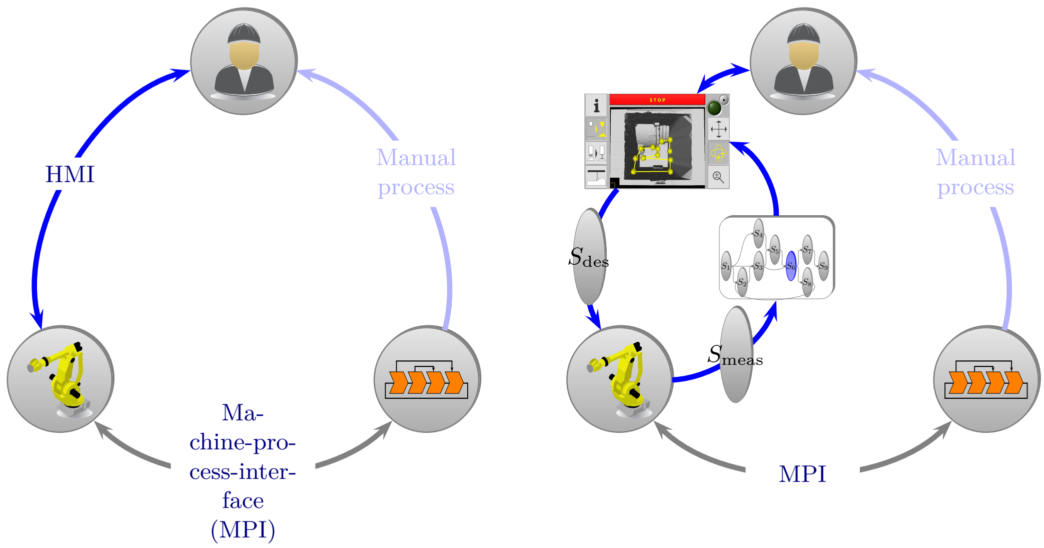
Figure 4.27 – Statecharts representation of the no-bake molding process (overview)

events will form the desired FMC situation (S_{des}) that is forwarded to the application on human operator confirmation. The action implementation is taking the desired situation and is translating desired inputs to equipment commands (e.g. Laser on/off) during action pre-processing. Equipment commands are forwarded to physical actions by the corresponding physical interface (e.g. TCP/IP) during the physical implementation. While physical actions are performed, sensor information are captured and collected to form the "real" FMC situation (S_{meas}). If all actions are finished, situation capturing and visualization post-processing is translating sensor information to HAI objects, which are feedback to the human operator.

For repetitive actions, such as tool change, no detailed information need to be provided operator, since these actions are mapped to meta-operators within the action space (Fig. 3.3) as illustrated in Fig. 4.26. This allows to reduce manual input to the absolutely necessary amount and supports human operator to focus on the central information rather keeping human operator busy with elementary inputs.

4.4.4 Overall process guidance and visual assistance implementation

Due to the rough environment of the no-bake molding application, robust devices are necessary. The chosen HAI is touch panel-based and especially prepared according to protection



(a) Semi-automated HAS **(b)** Implemented interaction concept

Figure 4.28 – Implemented control control concept for semi-automated HAS (Langer and Söffker, 2014)

class IP67. The process visualization is developed according to recommendations of

- VDI/VDE 3850 (2000) and
- DIN EN ISO 9241-210 (2010)

as introduced in Section 2.3 and adapted to touch panel-based interactions.

HAI-design

The realization of the HAI is illustrated in Fig. 4.29. The design is set up by having functional keys on the edges, which is reducing the overlap with the operators hands while interacting. The functional keys are locally separating primary and secondary functions. Referring to the process steps, primary functions are

- distributing mold material,
- impulse compaction of mold material, and
- leveling the mold surface,

whereas canonical manipulation is realized by secondary functions as

- zooming,
- rotating, and
- translating.

By selecting primary functions, meta-operators based on the proposed action space are released within the PCVS that are preparing necessary devices and auxiliaries for the corresponding process step, such as updating 3D measurement or preparing necessary tool.

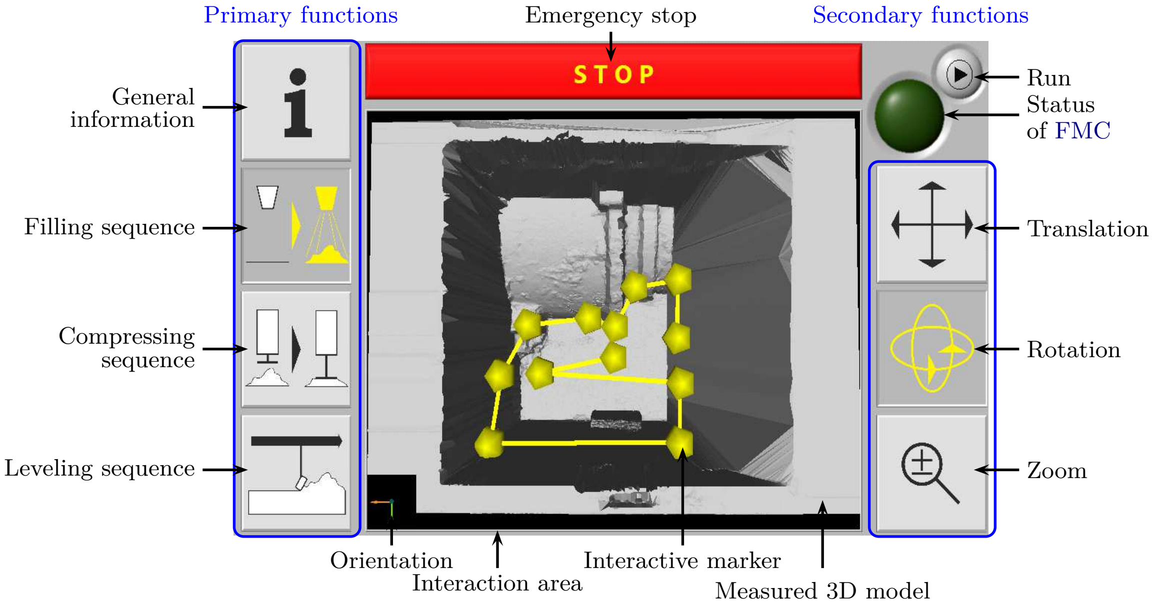


Figure 4.29 – Realization of the HMI
of the developed semi-automated manufacturing demonstrator
(Langer and Söffker, 2014)

These repetitive and inevitable actions (e.g. tool change) are performed without the necessity of any further confirmation of the operator. When entering a new process step (e.g. from filling to compacting), the spatial measurement is renewed and an actual scene is displayed centrally in the HAI with additional process assistance.

The spatial volume model (measured) of the mold cabinet is the main interactive object of the HAI. The visual model combined with the secondary functions for exploration are replacing the mold cabinet inspection by foot of the manual no-bake molding process. Furthermore, the spatial model is not only used for providing input abilities, output information are also mapped to the volume model. The representation of movements or locations of interests are visualized by markers (and depending on the active function also by additional pipes), that can be placed according to the process step scope.

Secondary functions allow for spatial exploration of the mold cabinet and to capture an overview of the cabinet's status. In addition, execution button ('play'-button) and status indicator are integrated into the HAI. With direct interaction, a desired process scene can be prepared and modified by the human operator. When the desired scene is finally prepared, the 'play'-button will translate the desired scene to input parameters (=meta-operators) and automatically applies corresponding actions to the FMC. The status indicator visualizes, if the FMC is done with the provided actions, however actions can be added continuously to already submitted desired scenes.

A major benefit of the proposed HMI design is the ability of visual robot programming (point and direct). The direct interaction is designed based on the manual process, while human worker have a direct 'look and feel'-feedback of the process. At least the "look" can be copied by the proposed interaction design. The available tools are adapted to interact with this virtual environment and in the interaction phase coordinate transformation are performed. The challenge of integrating the human operator into the semi-automated process and giving assistance is approached by keeping the flexibility of the handmade process in parallel to reducing manual actions to the minimum necessary.

Marker-based interaction technique

The proposed interaction technique is majorly using direct manipulation. Primary and secondary functions are available by soft-buttons at the HAI edges, as well as "emergency stop" and 'play' to provide desired scenes to the FMC. For operating single process steps, the human operator needs to have the ability to provide additional process information. In this function, "knowledge keeper"- and "process provider"-role of the human operator are of central interest. Knowledge about the locations of mold material distribution and compaction as well as an individual understanding of amount and intensity are core competencies to integrate into the proposed semi-automated HAS. Since the locations of actions (mold material distribution and compaction) to perform are varying over the cast part specific characteristics and process specific uncertainties, flexible input methods must cover for those ad hoc modifications. In parallel to the introduced tuples, a visual metaphor is introduced to represent their meaning.

The tuples with their information content are mapped to marker. A marker is a visual object that fits into the spatial scene with the intended meaning whether representing a point of compression, an interpolation point of distributing mold material, or start and final point for mold leveling. Hence, available marker types are

- filling marker,
- compaction marker, or
- leveling marker.

Filling marker are the visual representation of filling tuples introduced in Eq. 4.7, compaction marker are representing Eq. 4.8, respectively. In contrary, leveling markers are representing the direction of leveling movement as it is illustrated in Fig. 4.21d.

Marker-based interaction means the human operator to provide information by selecting marker type and placing marker at certain locations. This interaction methods is strongly connected to the available interaction device. In the underlying application a touch panel will only provide planar geometric information. The real process is taken place in spatial space, thus a mapping becomes necessary that is interfacing planar visualization of the spatial FMC. This is performed by coordinate transformation of the planar space (screen pixel coordinate frame) to spatial scene space (RahimiFetrati, 2010).

Compaction markers are created directly onto surface of the spatial volume model. The interaction method is realized by simply point and direct methods, hence the human operator is directly placing additional marker by double-clicking corresponding location on the model.

In contrary, filling marker and leveling marker are not visualized onto the surface. Filling marker are arranged in plan-parallel to the pattern plate. Thereby, the distance is fixed and determined based on the available filling height. The filling markers are connected by pipes according to Fig. 4.24. Hence, the filling and distribution is transparent to the human operator as the mold material mixer is towed along the implemented path by the industry robot.

Similar to filling marker, leveling marker are visualized in a plan-parallel plane to the pattern plate. Assuming a relatively simple movement to level the surface, this function is initially represented by a two-marker-movement allowing only minor adjustments as during a priori experiments, a single leveling slide is sufficient to level the surface. However, the human operator is still able to modify the direction of the leveling movement.

Common to all markers, a marker is mapping coordinate and functional information of the corresponding process step to a single visual image; an abstracted sphere. The technique to interact is also common to all markers

- placing marker – double tipping the spatial model will create a marker onto the surface (here, first and second tip position will be captured and a marker is only set, iff there are nearby. The second tip position will define the location of the marker set),
- moving marker – is a two actions process. First the marker to move will be selected by tipping it and the final location will be set by single tipping the new location,
- removing marker – is realized by double-tipping the marker to be removed.

In case of filling or leveling marker, the connections will be renewed after each step of modification of the human operator and are updating the movement route of the mold material mixer or the leveling rod, respectively. After finishing last modifications to the scene, the human operator has a direct feedback of the desired target scene and can provide the input parameters to the FMC by pushing the 'play' button. This action initiates the setup of the meta-operators and after a final confirmation by the human operator, the meta-operator is applied. The intermediate scenes that are surpassed during meta-operator execution are stored in a First-In-First-Out (FIFO) that is forwarded in the action space in order of occurrence. If the dialog is interrupted, the PCVS is returning to the interactive object for additional modifications. The modifications can include providing further process knowledge, adapting the target situation according to What you see is what you get (WYSIWYG) philosophy. If the human operator is done with providing additional process knowledge to the given scene, the meta-operator can be initiated and applied again by selecting the 'play' button.

Visual in-process feedback

As illustrated in CTT-analysis shown in Fig. 4.6, several sub-steps need to be performed in order to create a new mold. The interdependency of physical actions of the FMC and process guidance activity of the human operator on a top-level view are connected by human decision of the finishing status of the primary task (filling, compacting, and leveling). Hence, task-specific visual in-process feedback is necessary to support human operator SA and underlying decisions.

Filling and compacting procedures are circular connected as each additional mold material layer needs specific compaction. The status must always be transparent as the human operator approves for finishing each step. This is realized by updating the spatial model by 3D measurements not only to capture necessary input parameters for the automated FMC actions but also after each process procedure to show recent results to the human operator. The raw process feedback is extended with corresponding process guidance assistance.

Tab. 4.4 shows frequently occurring relations from CTT-analysis of the no-bake molding process and corresponding assistance measures. The primary functions are connected by

Table 4.4 – In-process assistance

Symbol	Relation	Assistence concept
>>	Release	Informative assistance: Warning for early cancellations. Supervisory assistance: Deactivating of optional actions until current task is completed.
[] >>	Release with information transmittal	Informative assistance: Warning if errors occurred during initial task. Visualizing suspicious errors. Supervisory assistance: Deactivating of optional actions until error is resolved.
||| / |[]|	Independent parallelism and parallelism with information exchange	Informative assistance: Visualization of optional actions in parallel to active current completion (status display).
[] / [>	Choice and Deactivation	Informative assistance: Recommendation for optional action with respect to successful task completion.

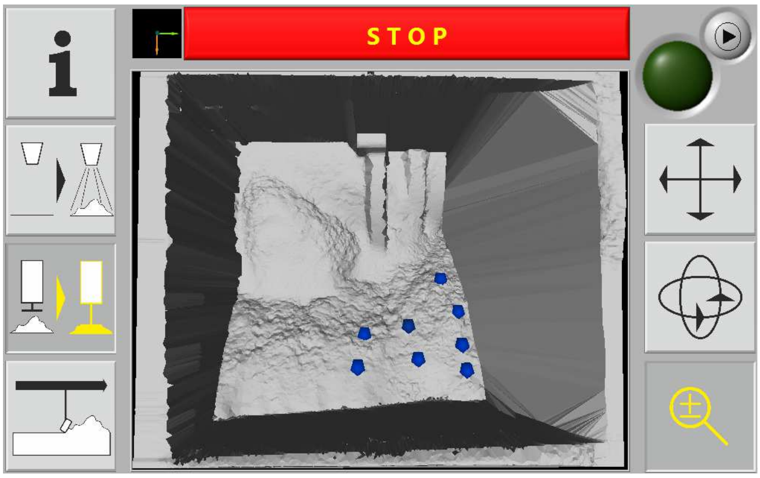
"release"-relation, meaning that finishing a primary function needs human operator approval. Human operator approval is based on a positive evaluation of the current process step result. Based on situated information assessing either

- filling procedure or
- compaction quality

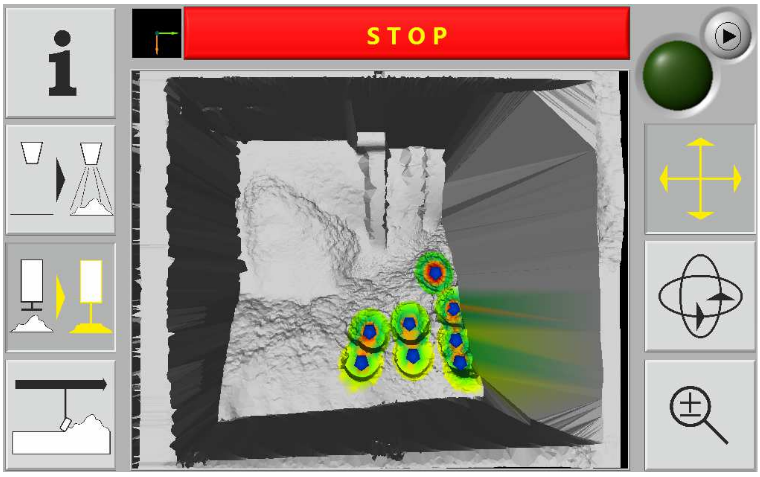
the corresponding information is visualized in HAI. In case of filling distribution evaluation, the spatial volume model is updated and always a new filling path is computed to let the FMC react immediately, if human operator decides to add another mold material layer. For assessing the compaction quality, a color-code is applied onto the spatial model and indicating areas of

- low compaction level,
- desired compaction level, or
- over-compacted level

by color similar to signal lights arrangement. The visual distribution of compaction levels within the FMC is illustrated in Fig. 4.30 and can be assessed by a single look onto the updated model. In complex cases the human operator can get a deeper impression of the achieved mold compaction distribution by using secondary functions while virtually navigating through the scene. The color-coded feedback to the human operator is providing assistance by setting additional compaction markers onto the model in areas of low compaction level. Due to the physical characteristic, over-compacted areas cannot be loosened up with the proposed multitool. However, direct in-process feedback of such areas with known spatial location within the resulting mold allow for early cancellation of the molding process in cases, where significant areas are non-optimal compacted. In other cases, the



(a) Input of compaction locations



(b) Visual in-process feedback of proposed compaction evaluation

Figure 4.30 – Operator input of compaction locations and feedback of in-process compaction quality measurements

human operator can decide from individual knowledge base, if the locally over-compacted volume element can reduce the resulting molds quality significantly.

4.5 Chapter summary

The manual no-bake molding process is analyzed using the HTA-based approach of CTT methods. The resulting overview of major and minor task and their structural interdependency is used as an input to an SOM-based representation and further mapped to statecharts. Common to SOM and statecharts representation is the capability of describing the macroscopic and microscopic process relations and corresponding interaction features of the overall HAS. Furthermore, a suitable task distribution is considered that allows to satisfy human factors in parallel to process constraints. The basis of successful process design is a detailed understanding of the fundamental process steps as e.g. mold material compacting. By advancing and combining available standard devices, such as impact cylinder, pneumatic auxiliaries, sensor equipment, a multitool is designed allowing the investigation of procedural cause and effects. The results obtained by automated mold compaction are evaluated by standard procedures widely used in casting industry and attest feasibility. The established characteristic diagrams are feed into the process allowing to automate frequently used actions and available reference results enhance the FMC to deliver in-process quality control. User guidance and process assistance is given by visual feedback and direct interaction with the HAI. The major benefit of the proposed HAS for no-bake molding is the strong commitment to standard equipment and even though complex auxiliaries are used, e.g. standard industry robot, no special requirements on human operator persists. Complex programming of the FMC is reduced to “point and direct” or visual programming. Therefore, the developed HAI is capable to represents real spatial measurements of the mold cabinet’s status and in addition, the marker-based interaction technique allows to efficiently map provided input parameters to the FMC. The knowledge and experience of skilled workers, where to provide which potion of compaction is integrated into the marker-based interaction method. The manual mold material distribution or complex joint-based remote control of active mold material mixer is also replaced by a marker-based approach so that the available expertise where to provide mold material is also mapped to marker-based visual programming approach. Essential process feedback is given by frequently updating spatial measurements and corresponding visualization as well as in-process quality control by color-mapping compaction-related measurements onto the spatial model for straight assessment by human operator.

Chapter 5

Initial user evaluation: experiments & results

The resulting prototype is an unique demonstrator that is initially evaluated according to user-centered approaches as introduced in Chapter 2. In order to realize an initial user evaluation of proposed assistance functions, two working groups from industrial companies were invited to take part on experiments.

5.1 Experimental setup

5.1.1 Scope of the experiments

The performed experiments have the scope of capturing direct feedback of experienced process specialists (user) with respect to usability and operability of the developed demonstrator. Especially, occurring issues that are related to the separation of human operator and/or the changed process sequence are of major interest and need to be detected.

The experiments are designed to get first qualitative results only and are intended to perform a revision on the initial design of

(i) the FMC itself,

(ii) the HAI, and

(iii) the guiding assistance given during process execution

as proposed by the usability approach detailed in Section 2.3.2.

5.1.2 Characteristics of test persons

Test persons from casting companies were invited to take part on usability experiments. The companies are chosen to be representatives of the manufacturing community using the no-bake molding technique. The distribution of the test persons ($n = 6$) represents two groups of two distinct companies with different seniority level as provided by Tab. 5.1.

The test persons are representing a bandwidth of cast industry employees. Employees of manual molding companies are characterized by an almost equal distribution of skilled laborer and career changer from different handcrafting industry branches, e.g. roofer or electrician. Also common to manual molding is the employment of unskilled workers that are advanced on the job by forming working groups with varying seniority level. Grouping skilled and unskilled test persons is also necessary, since in individual cases employees

Table 5.1 – Data of test subjects of user evaluation experiments
(number of test subjects $n = 6$)
(Langer and Söffker, 2014)

Gender	Qty.	Age [years]	Qty.	Seniority [years]	Qty.	Apprenticeship	Qty.
female	0	18 – 30	3	< 5	3	unskilled	1
male	6	31 – 50	3	5 – 10	1	semi-skilled	2
		51 – 65	0	> 10	2	skilled	3

may stay only for a single season with the company and need to be replaced every other season, which is cause and effect of the demographic change in Central Europe (refer to Section 1.1).

The test persons were split into two groups. The experiments were performed on separate days with no intersection of the group members and hence, no (known) information exchange after the first FMC assessment.

5.1.3 Experimental procedure

The experimental procedure is based on the following time line

1. introduction to the topic (slide show),
2. brainstorming about issues of the manual molding process,
3. introduction into the HAI (design and interaction),
4. offline experiments (refer to Section 5.2),
5. FMC assessment (refer to Section 5.3), and
6. interview and closing meeting.

The introduction dealt with basic information of the goals and the actual status of the underlying research project “semi-automated no-bake mold manufacturing”. The intention of the subsequent brainstorming was to gain feedback about the individual sensation of the professional’s with respect to their daily business and to collect information about fears and chances. Afterwards the HAI was presented and a big picture of its capabilities was given.

The test persons were individually performing the proposed HAI evaluation (Experiments I-III). Each test person had the chance to initially freely interact with the HAI without any restrictions (about 10-15 minutes). Then, the official experiment was engaged (refer to Section 5.2). After all test persons were finished with the individual experiments, the entire group was confronted with the real FMC. Each test person had the chance to use the FMC in order to fabricate a real mold. The FMC assessment is intended to diclose, how the implemented process guidance features are accepted by the test persons. Thereby, based on the available analysis and the development in cooperation with process experts, the process guidance assistance is implemented referring to the variable of interest approach (refer to Section 3.3.3). Hence, depending on the actual FMC scene (situation), process guidance is given with respect to the active process step. This means, achievement of optimal filling is intended to be reached by autonomous filling path computation and corresponding visualization, for achievement of optimal compression the compaction marker locations and corresponding compaction level visualization, respectively. The visualization is the central instrument to support human operator situation awareness in making the entire process (step) transparent and provide process information in an amount that is necessary for process decisions. The final closing meeting and interview provided an overview of human operator needs during process execution, when interacting with the FMC. Furthermore, valuable input for further improvements and future work was generated.

5.2 Offline usability experiments with skilled employees

Prior to the experiments with the FMC, both groups had individual off-line training to get used to the look and feel of the touch screen-based HMI (refer to Fig. 4.29). Referring to Fig. 5.2 and Fig. 5.5, each test person was facing

I) a set of scene screenshots and was asked to copy the printed scene from initial object orientation to the desired target object orientation to the HMI by manipulating the 3D volume model using secondary functions (refer to Section 5.2).

II) After that each test subject was asked to copy a set of interactive marker onto the 3D volume model (refer to Section 5.2) as well as

III) to improve a systems default of a mold material distribution path that was preconfigured prior to the test setup (refer to Section 5.2).

During the experiments usability issues for secondary functions (refer to Fig. 4.29) are of central interest and are investigated based on time consumption during interaction and quality of the result (direct comparison of user solution to the given scene configuration).

In contrary to working procedure that is common in factory, which means working in small teams of two or three persons, test persons were tested individually according to the experimental design.

According to the performed experiments (I-III), the test persons were observed and monitored from the perspective of time and quality of the result. Performance measurements were taken manually without professional equipment as it is usually applied in HMI evaluation (e.g. eye tracking, etc.).

Experiment I: Canonical manipulation

Canonical manipulation means orientation and navigation in a virtual environment. In the proposed application, canonical manipulation means investigating the spatial model for reasons of process monitoring and quality assessment by the available input abilities (secondary functions).

An illustration of the experiment is shown in Fig. 5.1. The test persons are directly interacting with the HMI and manipulating a given initial setup (Fig. 5.2a) to yield given target setups (Fig. 5.2b-Fig. 5.2f). The mean, minimal and maximal performance of the test persons in combination with the given set of orientations is captured and documented in Fig. 5.3.

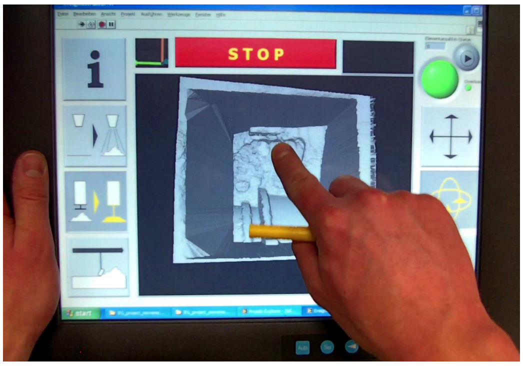


Figure 5.1 – Canonical manipulation of measured mold cabinet

The overall results of the initial user evaluation indicate, that copying the first four scenes is easily performed by the test persons. Orientation 5 is showing a zoomed perspective of the inner mold contour, which lead to an remarkable amount of additional identification time.

Regarding experiment I, the test persons solved all tasks of positioning the 3D volume model within the 3D scene in a reasonable time (some seconds). However, one task was to zoom to a specific detail of the pattern contour (refer to orientation 5), which some of the test persons were not able to identify immediately in the global view. Once the identification process was finished, canonical manipulation lead also to an reduced accuracy compared to Orientation 1–4.

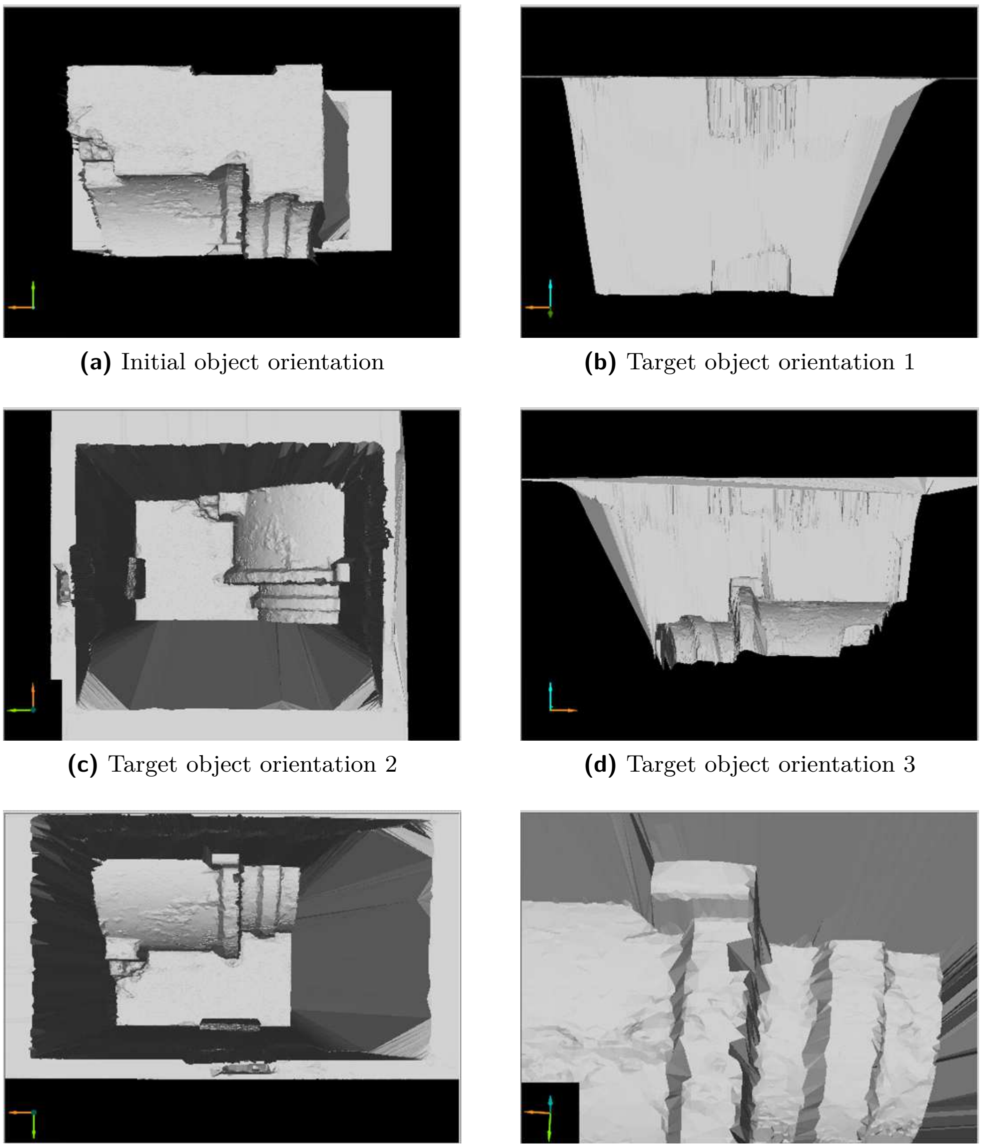
Apart from recognizing the mapped information and the represented virtual model, the test persons gained confidence and improved their skills in interacting with the interface as it is indicated by the trend given in Fig. 5.3.

Experiment II: Creating marker and correcting marker location

Since marker are focusing the fundamental input information, placing marker and correcting their positions is an essential interaction procedure that will frequently be performed by human operator. As introduced in Section 4.4.4, providing marker is a straight forward way to include human operator's process knowledge into the HAS (refer to Fig. 5.4).

Experiment II is designed for placing compaction markers onto an empty flask. The test persons are asked to provide five compaction markers on pre-defined positions. The positions are illustrated in Fig. 5.2. Placing marker is performed according to interaction methods detailed in Section 4.4.4. In this first instance of the experiment, corrections of marker locations were forbidden.

Underlying performance measures were captured by tracking the distance between pre-defined marker locations and the provided marker locations and the corresponding time that was necessary for the test persons to provide all marker locations. All test persons solved the task with an appropriate precision. Even in cases, a marker was set to an imperfect position (compared to the task and subjective for the test person), the obtained distance measure was evaluated to be relatively small compared to the physical model dimension.



(a) Initial object orientation **(b)** Target object orientation 1
(c) Target object orientation 2 **(d)** Target object orientation 3
(e) Target object orientation 4 **(f)** Target object orientation 5

Figure 5.2 – Experiment I: initial and target situations for usability study on secondary functions of the realized HMI (Langer and Söffker, 2014)

Experiment III: Improving system assistance for filling path optimization

In the third offline experiment, the test persons were asked to improve a given process assistance for automated mold material distribution. There was no restriction on the filling path to provide.

According to Section 4.4.1, the path was not optimized with respect to jerk or accelerations. In contrary, the standard path was displayed, that is realizing a back and forth movement over the entire flask area. The provided filling distribution would result in an (almost) homogeneous layer onto the flask plate. The corresponding improvements that were suggested by the test persons are shown in Fig. 5.2.

Major feedback gained from this experiment was the lack of completely denying the assistance recommendation by direct interaction. The results are illustrated in Fig. 5.7. The

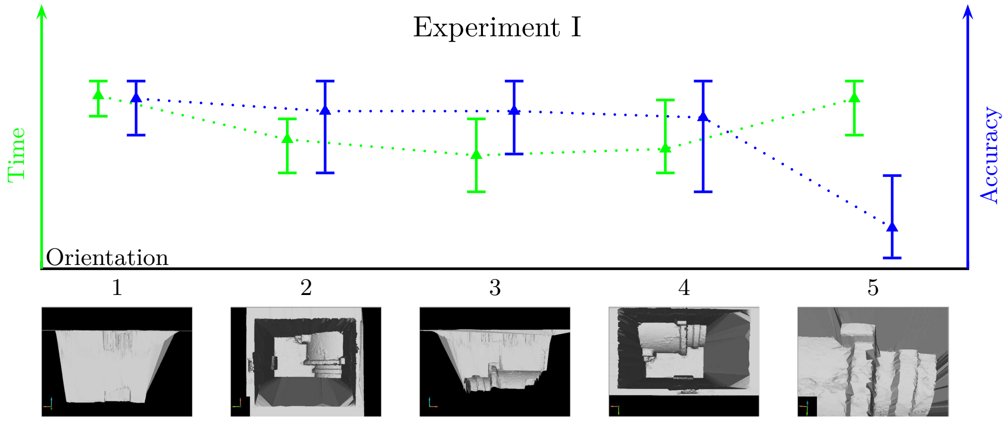


Figure 5.3 – Qualitative results of Experiment I (Langer and Söffker, 2014)

output of the assistance is shown in yellow and the (redrawn) results of the test persons are shown in red. Obviously, some test persons preferred to cover the mold model first, others filled the cabinet evenly (as provided, however they preferred to do it layer by layer).

Experiment III discloses most varying results with respect to the provided process information of the test persons. Since, the experimental procedure was performed completely decoupled from the real FMC, the obtained results spread did not tend to any special filling path. The provided individual optimum (without any sample given), is spreading over different companies (this was manifested by the interview afterwards). Furthermore, the obtained results are evidently showing significantly different process understanding of the test persons.

This experiment was repeated online, hence coupled to the FMC. In this experiment, test persons mostly accepted (5) the assistance that was proposed by the HAI (refer to Section 5.3).

5.3 Flexible manufacturing cell evaluation

The offline experiment were intended to give first feedback on the prototype of the HAI. Online experiments are intended to gain understanding of additional human operator needs

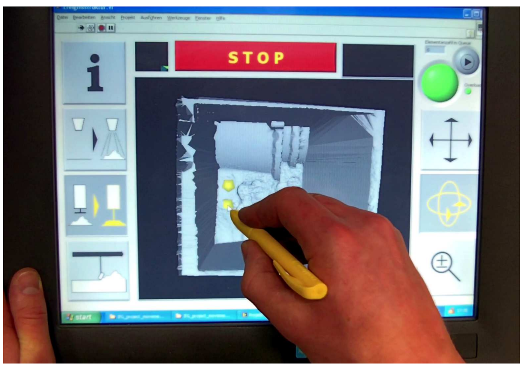
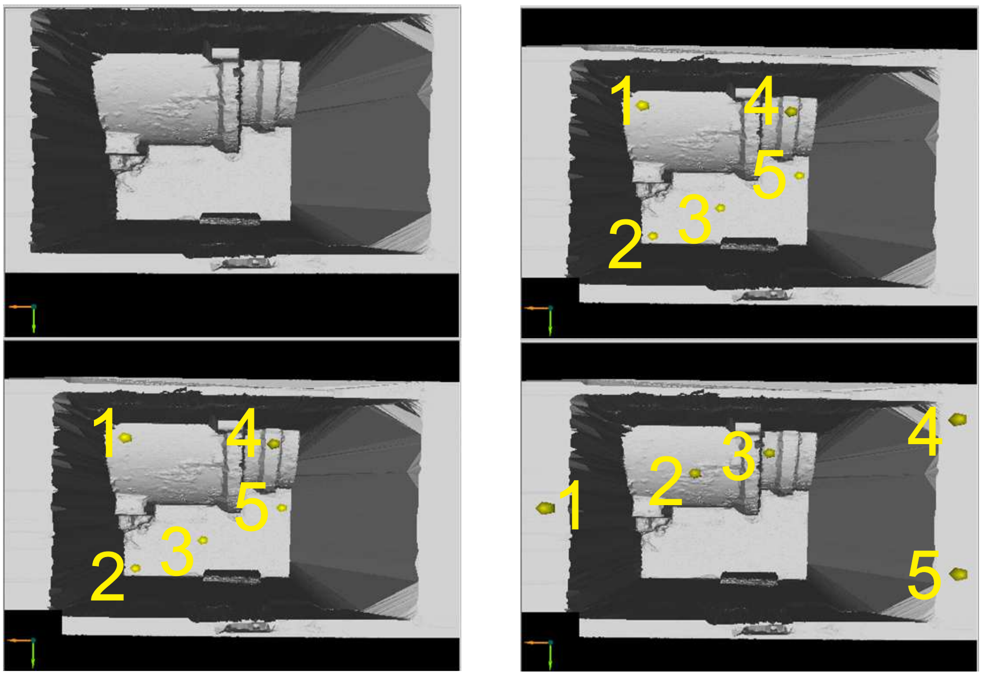


Figure 5.4 – Creation of compaction marker by direct interaction



(a) Initial scene (top) with added compression marker (bottom)

(b) Initial marker setup (top) and shifted marker (bottom)

Figure 5.5 – Adding and manipulating compression markers for usability study on secondary functions of the realized HAI (Langer and Söffker, 2014)

in dealing with the FMC prototype.

Review on evaluation procedure and test constraints

All test persons were interacting with the semi-automated HAS, in order to get an individual look and feel feedback of using the FMC. The online experiment afterwards was also performed without any detailed supervision of the test persons with eye tracking or video capturing. Furthermore, there was no detailed task given to the test persons.

In order to receive a macroscopic feedback of the proposed manufacturing approach, the experimental design was left open. The only task, the test persons were ask to perform, was "creating a mold". However, when interacting with the FMC, incremental assistance by the pre-defined action space was given based on the "variable of interest"-method.

The objective was primarily on the process execution and the evaluation on the interaction technique, and not on the achieved homogeneous mold rigidity. Latter test would be an ideal assessment of the achievable mold quality using semi-automated manufacturing, however this was not in focus.

The experiments were performed without detailed supervision of the test persons with e.g. eye tracker or video camera. Qualitatively, the incremental assistance by the predefined action space supported the test persons to focus on the next process action and corresponding process supervision. In Fig. 5.8, some pictures of the test persons interaction with the FMC are given. The user assistance was only providing mold material distribution path. Color-coded feedback was not available in the online experiment during this stage of the underlying research project.

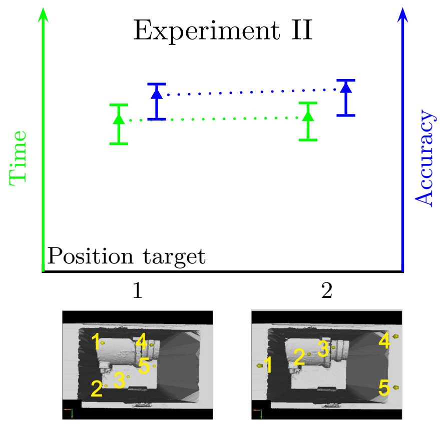


Figure 5.6 – Qualitative results of Experiment II (Langer and Söffker, 2014)

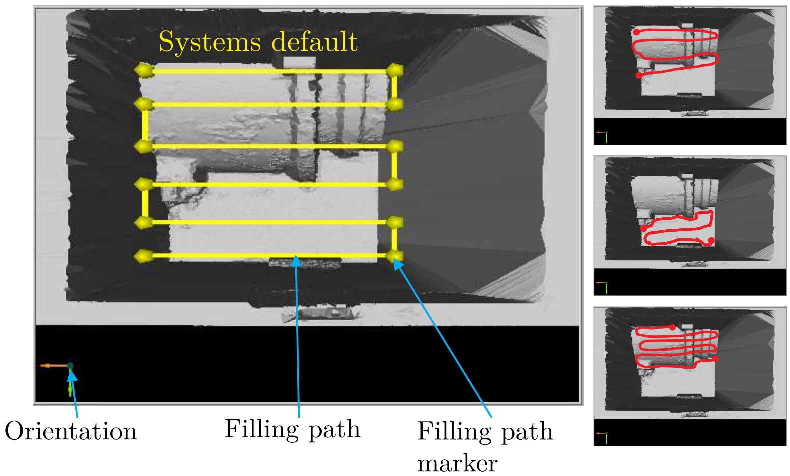


Figure 5.7 – Experimental results of mold distributing assistance with skilled employees (red), systems default (yellow) (Langer and Söffker, 2014)

Even though there was only a short training session. Each test subject evaluated the semi-automation mold manufacturing cell and its functionality as suitable and helpful approaches in their working environment. The lack of look and feel was confusing at some instances during the evaluation due to missing feedback of the HMI. However, the visual feedback was sufficient to finish the process. A general conclusion according the molding process is summarized in Tab. 5.2.

User feedback

User feedback was collected during interviews with isolated test persons (after offline experiments) and additionally after the online experiment with all test persons together. During the individual interviews the test persons mentioned several aspects to improve the HAI, such as

- the order of marker approach is not visualized, however user's like to know where the systems is beginning, where it is currently, and where it will be stopping when performing the process,

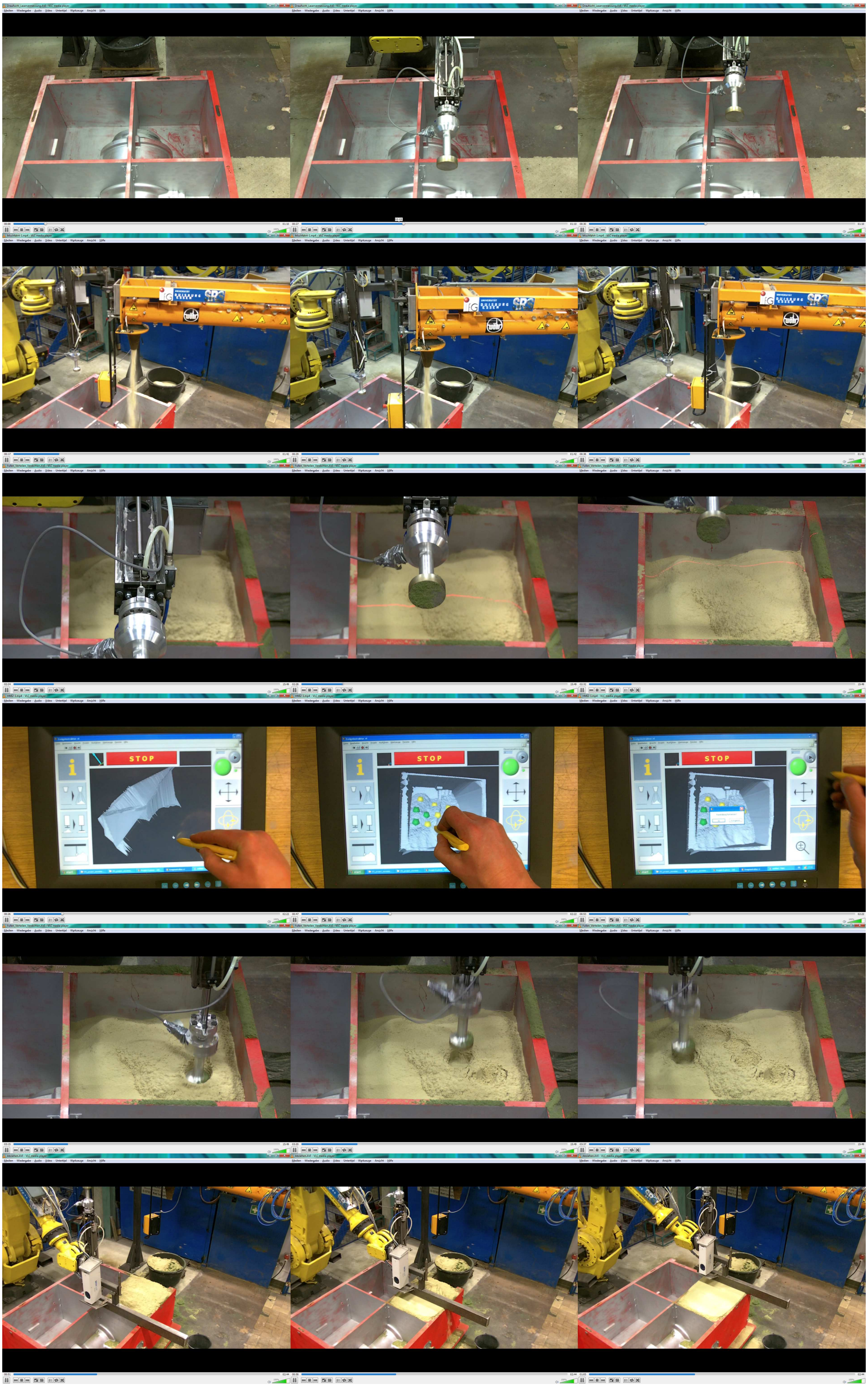


Figure 5.8 – Picture story of initial user evaluation

- the robot is not visualized, however operator may need current pose outline of the robot,
- there were doubts in interacting with the system under real conditions (wearing gloves, dusty environment), so some (2) of the test persons preferred to use a stylus to provide inputs and
- several process actions that need to be performed in parallel, e.g. inserting chills or piping are not mapped to the demonstrator.

Additionally, test persons were also aware of the potential of the demonstrator with respect to their working routines in factory, such as

- an improved control of the mold material mixer that is usually remotely controlled based on the two circular joint positions, which is challenging and needs a lot of practice in order to perform specified paths or straight movements,
- no need to step into the cabinet and no further need of PPE,
- feedback on the mold rigidity and a traceable feedback from rebuilding concerns to improve mold quality, or
- less physical intense work.

Concluding from the test persons feedback, several improvements on the overall HAI can be deduced. The mentioned points related to the FMC itself are connected to programmatic features of the HAI, that are simple to implement. The critic given to the touch panel device and interaction method (finger or stylus) is an open point that need to be evaluated in real factory environment. Besides the suggestions of HAI improvement, the test persons were aware of the FMC benefits to human worker that will manifest in factory.

5.4 Chapter summary & discussion

With the proposed FMC and the underlying framework, requirements on reproducibility of mold material compaction, process status and guiding visualization by using an advanced HAI and intuitively learnable interaction techniques are fulfilled. In parallel spatially decoupling of manual activities and no-bake molding process are realized. The evaluation of the FMC lead to reasonable results with respect to the operational and technical solution and confirms feasibility for semi-automated no-bake molding.

Transferability into casting application

Under the assumption that mold quality is strongly related to compaction quality, which is evaluated by pre-experiments and by the experiments performed within the scope of this work, the developed HAS allows decoupling individual process understanding of human workers and resulting mold quality. In-process quality control is realized by combined force-stroke measurements and corresponding assessment of achieved compaction stiffness that is equivalent to mold material compaction quality. Latter fact is proven by systematic field experiments of different geometric and process dependent contributing entities using standard equipment that is typically available in casting company environments. Furthermore, the developed technical solution replaces manual physical actions and enables the operator to capture real-time process feedback.

Even though, the proposed results are close related to the applied conditions, such as chemical recipe and quartz sand quality, the obtained solution is applicable without restrictions to different process setups. Mandatory for the application to a different process setup is renewing the parameter study and the implementation of the obtained results into the algorithm of the PCVS. According to the functional design of the compaction tool and the obtained results, force and stroke measurements deliver redundant information, hence force or position sensor may be removed to reduce investment and maintenance costs. In addition, reducing the complexity of the compaction tool by removing e.g. force sensor would allow optimizing the available space and more compact tool design. Hence, improving the tool dimension may lead to an extension of the applicability within the manufacturing line-up.

Features like the automated filling route determination can be transferred without any restrictions assuming that optical measurements can also be implemented. Since state-of-the-art molding material mixer are manual remotely controlled based on joint coordinates, direct manipulation in Cartesian coordinates and automated mold material distribution based on provided input paths is a major benefit of the developed FMC. Especially, this proposed feature turns out to be appreciated by the test persons during the performed usability experiments.

Mold material compaction

Common practice in no-bake molding is the manual distribution and compaction of the mold material. Depending on the mold dimension, experienced worker perform compaction actions with or without additional tools. For the resulting cast part, the mold compaction and thus mold quality is of vital importance that is subject to variations and uncertainties caused by the lack of reproducibility of the manual process and varying workers. The spectrum of the resulting quality contains cast parts with elaborate rebuilding concerns up to rejects that are not worth enough to rebuild.

The validation results of the compaction tool are proving the reproducibility of applied compaction energy and the corresponding achievable mold material rigidity. As provided by the experiments, the realized bending rigidity of automated compacted bending bars is of the same scale as for the manual fabricated ones. The applied compaction energy and measured mold material stiffness can be tracked and assigned not only to a mold but also to the resulting cast parts and its casting defects. The gained feedback is unique in no-bake molding as of today[1].

Within this contribution the spatial stiffness distribution within the mold is captured. Especially, the stiffness distribution of the mold parting line is a valuable information when aligning this information with occurring defects.

Quality assurance assistance

Spatially decoupling is not only applied to satisfy human factors, but also as chance to introduce quality assurance assistance alongside with the integration of human process knowledge. In the manual process, mold material compaction is hard physical work that is

[1] This work is based on profound literature study which is not including any evident of a comparable apparatus.

mapped to the compaction tool. Based on the performed process analysis, human worker expertise lies in the knowledge of where to apply compaction and assessing the compaction status. Both, providing compaction locations and overall compaction assessment is still the responsibility of the human operator, however the applied compaction energy is determined based on empirical coherences.

Valuable process information is still necessary in order the FMC to operate, however the determination of mold material filling volume and corresponding location dependent impulse compaction energy are determined based on the available characteristic diagrams, hence independently of the individual human operator. The assessment of the achieved compaction quality (equal to mold and cast part quality) is prepared and visually presented to the human operator for final approval or manual intervention.

Reflecting the experimental results certain restrictions apply e.g.

- the obtained characteristic diagrams are captured using standard mold sand (quartz sand, H32 granulation), in factory recycled mold sand with a concentration of 5 % of new sand is typically used or
- the compaction experiments are performed with coplanar setup only. Effects occurring due to off-coplanar impulse compaction on pedestals, domes, or similar geometric pattern contours have to be determined.

Besides these restrictions, the available results are evidently illustrating that the achievable compaction quality is reproducibly and controllable.

Visualizing and interacting process information

The interaction with a spatial model and the available process step-related interactive marker as a hybrid form of input-output visualization object were recognized positively by the test persons during the usability experiments. Especially, test persons mention the straight forward interaction concept in combination with the developed FMC to have potential to support their daily work. The evaluation results principally confirm the feasibility with respect to usability, process guiding, and understanding that will also be beneficial to the company with regard to cost and time consumption.

The direct manipulation is accepted by the test persons, however several suggestions were collected such as some test persons prefer to use stylus instead of using finger for interacting the HAI, or the HAI is not showing the actual pose of the robot within the illustrated virtual environment. Both suggestions are available improvements to the HAI and need special investigation in order to determine additional benefit.

The test persons confirmed the benefit of illustrated process information and identified possible and suggested operation options. From the test persons perspective, the allocation of mold material distribution paths and compaction location is a major improvement for daily working routines, however the implemented features are not sufficient to exclude disaffection with respect to loss of control. Especially, the compaction sequence could not be adjusted to human operator's understanding. Thus, the "compaction plan" is not optimized and followed no special sequence, whereas the filling path is optimized with respect to jerk of the robot. The HAI at this design level is not offering any choice of how to deal with sequences, which will need to be considered in future HAI evolutions.

The traffic light metaphor to highlight compaction areas with respect to their compaction quality level is appreciated by the test persons. The implementation is criticized as in the evaluated HAI version, the rendering is not distinguishing between surface areas that are representing pattern or sand contour. This issue is addressed by a detection module that is comparing previous cabinet situations to actual cabinet situations in order to determine filling areas (Schmidt, 2013).

Usability perspective

In general, the underlying research needs further investigation in the real process environment, for which the demonstrator needs to be transferred to a factory and aligned with the established product line-up. Especially, influences of cast parts geometry to process describing variables needs detailed verification. With respect to the proposed guidance assistance, further evaluation with skilled employees will lead to a more acceptable HAI design and can be used to improve the available training material that was used for the presented user study. Hence, there is the need of designing experiments leading to resilient and measurable performance indicators of guided and unguided test persons and feedback of the resulting mold quality.

Visual programming is a major benefit that allows complex technical systems such as the proposed industry robot to be used within industrial environments. No special education is necessary to operate the proposed FMC, the user study supports that the performed training is sufficient to start working with the FMC. The interaction method itself was evaluated to be beneficial, however doubts on the chosen technical solution and the corresponding appropriateness for cast industry environment will need additional confirmation that was out of scope of the performed experiments.

Representative evaluation of interfaces is difficult due to the small number of test persons. Comparable studies for detailed evaluation and analysis is performed by considering a multiple of the amount that is presented in this thesis. However, with respect to the amount of employees of representative companies, the number of test persons is representing almost 5 % of the typical employee size of the company[2].

Concluding from the employee's feedback, none of the test persons were rejecting assistance functionalities as filling path offer or automatically compression energy determination. Even though only relevant information were displayed accordingly to the proposed information filtering methods and prioritization of process relevant characteristics (mold sand stiffness), the test persons were distracted from the moving parts within the manufacturing cell that sometimes lead to faulty insertion by accident. Concluding from the experiments, there is the need of analyzing and implementing of attention attraction methods (Wu et al., 2005) and to concentrate even more on user-centered design approaches (Zühlke, 2004) of the HMI.

The direct comparison of the traditional and the proposed manufacturing process with respect to several disciplines such as process control, occupational safety, process quality, or similar genres is summarized in Tab. 5.2. The overall statement can be given as the proposed framework has a promising potential for the realization as state-of-the-art.

[2] Referencing the total amount of employees may not be representative for the manual molding branch, meaning that the real number of manual molding employees referenced will lead to a percentage of 10 % to 15 %.

Table 5.2 – Comparison of the proposed framework with respect to traditional manual manufacturing.

Discipline	Proposed framework	Traditional handcrafting
Process control	Easy to implement as predefined procedure	Human-regulated process with high flexibility, but not repetitive and hard to be quality controlled
Occupational safety	Human and process are separated leading to less safety or personal health concerns regarding the noxious environment, however there is potential risk introduced by the automation.	Personal protective equipment is mandatory due to chemicals and fine dust present in the process
Process quality	Improved due to in-process feedback of process-quality related variables (such as compression quality)	Employee-dependent leading to individual rebuilding concerns
Human factors	Workload is marginally reduced as the industry robot is performing all physical actions within the manufacturing cell.	Employees are subject to high physical workload, when manual compressing mold material or distributing mold sand while walking through the cabinet.
Product quality	Cast part quality is strongly related to mold quality, that is manufactured supported by automation. Automation is increasing the repeatability of the compression based on the captured sensor feedback. This makes an in-process quality feedback possible.	Mold quality is strongly related to specific employee that is responsible for the compression. Missing feedback leads to individual rebuilding concerns that are hard to trace and unknown rebuilding concerns.
Process assistance	Assistance is given in two ways, in guidance through the process and in providing situation dependent information of interest to support the human operator in the role of quality controller and related decision situations.	No assistance is given, thus the process procedure is realized according to the individual human operator and their subjective process understanding.
Flexibility in manufacturing	The proposed flexible manufacturing cell is capable to deal with drags or cores of various geometry. However, secondary handling such as providing chills need further improvement of the proposed automation solution.	Skills of human operator, especially the fine motor manipulations, when handling chills or implementing the pouring system are sophisticated and are not completely replaced by the proposed approach.

Chapter 6

Summary, limitations & future work

The scope of this research is to establish a procedure for the automation of manual process that need to incorporate human skills and the development of a corresponding HAI that allows to still include the human operator into the HAS. The resulting semi-automation approach is verified on a reference application, no-bake molding and discussed from an HCA perspective. Automation of handcrafted processes is challenging with respect to procedural constraints and available technologies. This work deals with common practice of Human–centered design (HCD), incorporating task analytics, extended by model-based information collection and filtering, and applied to a classical mechanical engineering application. The resulting achievements, the gained benefit with respect to process and human factors are summarized and given assumption are turned into limitations to manifest issues for the future work.

6.1 Summary

As projected in the introduction, human contributions to technical processes are valuable e.g. with respect to flexibility in manufacturing or process quality from the resulting products and human factors perspective. However, with lack of reproducibility, processes are subject to the skills of the individual human worker. Under the constraint of demographic issues, this resource (meaning human worker with corresponding education) may not be available in future. In applications with unknown process descriptions and with the condition that process knowledge is not documented at all, the introduced framework and its application to the underlying sample process, the no-bake molding process, allows a representative demonstration of the feasibility of the developed approach.

Declared goals of this thesis are

- development of a demonstrator for semi-automated mold manufacturing according to the no-bake process,
- realization of a HAI to the HAS that is providing process (guidance) assistance and that allows to input process knowledge of skilled personnel, and
- testing of the system for applicability to the real process and with respect to real operating environment

while satisfying application requirements, e.g. of being

- flexible in terms of process requirements such as variety of products,
- adaptable to company specific needs, or

- human-centered such that no special training or education is mandatory for the human worker to use the developed demonstrator.

The SOM is used to establish an integrated model of a HAS serving as basic framework in order to achieve the required flexibility. The proposed event discrete approach allows the realization of user assistance of complex technical processes based on information filtering methods and is implemented based on statecharts. The proposed approach relates available information to formulated tasks and reduces model-based information to subsets of interest (e.g. variable of interest approach, which is focusing on compaction quality as representative of mold quality). The reduced information sets are used for situational assistance by improving the user's situation awareness and allow situational guidance of technical processes based on visual in-process feedback of process quality (compaction quality distribution).

Details of the proposed approach, major achievements, and benefits from either the process perspective or the human factors point of view, are detailed in the following.

- HCD is common practice in user interface design of computer application and rarely used in automation environment as far as referring to classical mechanical engineering applications. The extension of HCD to HCA is performed by incorporating approaches of interaction techniques and information selection method into the entire HAS. Successful process completion is related to the overall HAS design. Here, usability approaches are of central interest, especially when human worker need to be included into the process. Since semi-automation needs the HAS to perform automatically under human guidance, the interface is in the focus of the overall process design and subject to environmental constraints.
- Process knowledge is of major importance for a successful HAS design, however typically no documentation is available when handcrafting is considered. A detailed process analysis for the underlying application is performed that uses tools such as HTA and more sophisticated approaches such as CTT. The resulting representation of the process is used to identify process variables that represent process state and its success, referred to process quality variable and interconnections of process steps. In addition, field experiments disclosed characteristic diagrams to track process quality to be used as in-process feedback to the human operator.
- The entire handcrafted process is modeled by the SOM methodology and mapped into an action space of the FMC that is representing all reasonable states of the HAS. Within the action space, the human operator is source of events in order to release situation transitions. On a top level, the human operator is guided by the PCVS that is providing reduced information set when needed based on the variable of interest approach. This approach is visualizing the process quality representing variable to the human operator as color-coded texture map or marker-based action representatives within the PCVS.
- Major achievement and benefit of the presented research is the PCVS, which in its core is developed around the central information exchange object, a spatial model of the mold cabinet. The virtual representation of a fraction of the process environment allows the test person to use the demonstrator (FMC) after a compact introductory session; a benefit of the introduced marker-based visual programming-approach. Furthermore and according to the skills that the human worker developed in their daily work, process knowledge can be provided by direct interaction. Thus, mapping of handcrafting procedures to inputs to the PCVS is successfully performed by test persons.

- Satisfaction of human factors with respect to physical labor and exposition to crucial environment is realized by introducing the FMC with the industry robot performing all physical actions and spatial separation of human operator and physical process, respectively. Common programming routines of the industry robot are replaced by visual, direct manipulation programming. The implementation is realized based on marker. Marker are tuples of robot poses and physical actions to be applied according to the selected marker type. Marker-based programming in combination with the PCVS allows technically inexperienced workers to directly enter the proposed manufacturing approach. Latter fact is proven based on usability experiments with representative groups from factory. Summarizing, the proposed method improves occupational safety compared to traditional handcrafting.
- The proposed process control is based on an algorithm evolved from HTA analysis. Additional process guiding is realized by the "variable of interest"-approach that is also evaluated qualitatively with test persons leading to reasonable results. The "variable of interest"-approach is an information filtering method that is evolved from the action space, an event-discrete representation using SOM.

The experimental results were only evaluated qualitatively but show some important aspects related to upcoming extensions. In Fig. 6.1, the improvements to the traditional manual process and the semi-automated approach proposed by this research are visualized based on obtained results and discussion of Section 5.4 (also refer to Tab. 5.2). Major benefit by the introduced semi-automation lies in the process assistance which is contributing to a reproducible process and product quality and enhances occupational safety and human factors. Process control in the first attempt seems to be more sophisticated as direct feedback (look and feel) is interrupted and interface design and interaction technique is only evaluated with a small number of test persons. Flexibility in manufacturing of varying cast parts molds is about the same order for both processes and limited only by available technology or amount of handling devices.

Summarizing, the SOM information prioritization methodology is successfully applied to an engineering (mold manufacturing) example and tested with skilled employees in order to show performance of the method. Performed experiments show reasonable results in the sense of process guiding and task achievement by pointing out differences in the individual process understanding of test persons.

6.2 Limitations

In-process control and visibility of process parameters is not available in current manufacturing systems. The test persons confirmed in the individual and group interviews the valuable contribution of the developed technical solution to the no-bake molding technique, however the demonstrator is subject to a variety of limitations.

From a process perspective, the further essential process actions cannot be performed by the demonstrator.

- The implemented handling procedure with a single industry robot is only capable of manufacturing simple pattern geometries, such as drags or cores. Sophisticated handling devices are necessary for manufacturing copes or to include the manufacturing of molds that need chills or cast piping.

- Due to the complex geometry of the multitool, restrictions on the reachability exist that are depending on physical dimensions and shape of the tool with respect to the geometry of the mold to be produced.
- The multitool itself consists of several standard equipment that are operating with certain limitations. The 3D sensor will only capture contours that are free from undercuts. Thus, complex pattern shapes cannot be detected by the implemented capturing procedure. Due to the flexibility given by the FMC, the capturing procedure could be enhanced to e.g. consider scans from different perspectives. The compaction tool is over-sensing compaction quality, hence position sensing while impact compacting may be sufficient. The working frequency is limited by the pressure to be used for impact compaction, the more the load pressure is the less the impact frequency, which effects the mold manufacturing time and thus the recipe.
- From the mold material experiments, proof is given that the level of compaction can be related to bending rigidity of the mold material under given conditions. The statement that cast parts quality majorly depends on mold quality and mold quality is related to bending rigidity, is taken from available literature survey. However, a proof of this entire chain is not provided in this work.
- Usability experiments are performed with respect to feasibility and initial improvement collections. The obtained experimental results are only representing qualitatively the suitability of the proposed semi-automation and process guiding approach.

From a methodical perspective, a detailed analysis of the integrated HAS is a necessary step only rudimentary included in the proposed thesis.

- Usability experiments show reasonable results in terms that test persons only needed a

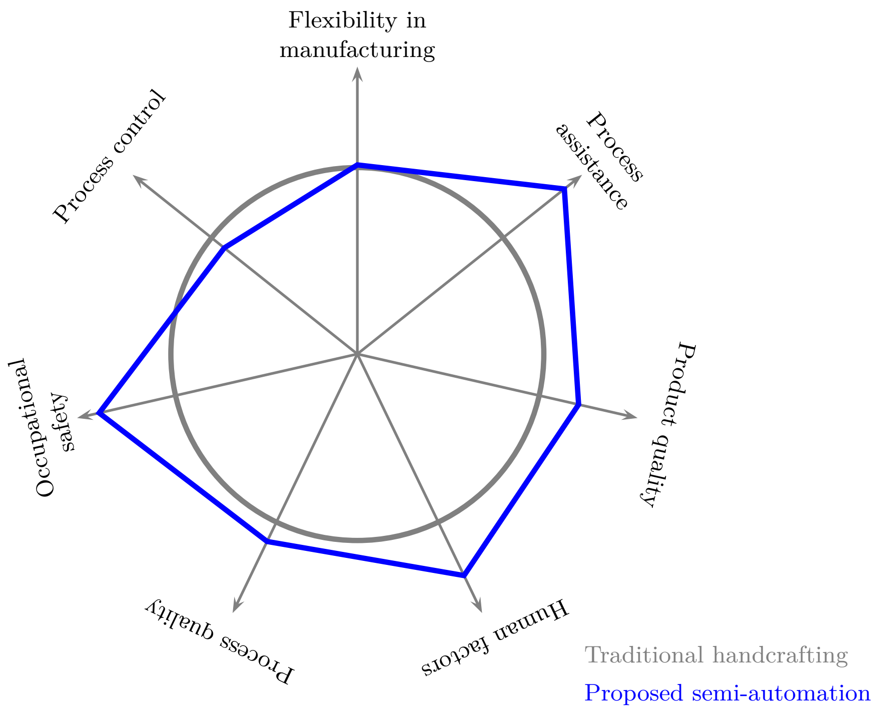


Figure 6.1 – Levers for future work

compact training session in order to get started with the HAI. Detailed analysis of the proposed HAI need to be performed to enhance the interface design and interaction technique.

- During evaluation of the FMC, test persons directly mapped features of their daily manual work to the proposed features of FMC. If input actions led to physical movements and corresponding sounds of the FMC, the test persons were distracted from the industry robot to move. This fact may be resolved, when human operator get used to the proposed manufacturing method, nevertheless this kind of distraction might be a source of potential risk for and also caused by human worker that are not directly involved in the FMC operation, but have their working place somewhere around.
- As introduced, HAS are subject to several labor psychologically motivated questions, such human worker acceptance, trust in automation, or shared responsibility that have not been part of this thesis.
- The developed FMC is evaluated with a single pattern representing typical shapes of mold patterns, however not representing the full spectrum.

As stated in Section 2.5, recent HAS research approaches are not considering the entire chain of automating especially handcrafting processes that are characterized by intense human-process relation as they exists e.g. in tube welding, upholstering, or no-bake molding processes. Thus, incorporating human skills and experiences or process knowledge while automating processes with the aim of keeping human operator integrated in the resulting HAS is not of special interest. This thesis combines cross-sectional approaches beginning with process analysis using HTA or more sophisticated CTT, over interactive HAS modeling using an event-discrete representation SOM as framework for process guidance and supervision assistance and deducing information of interest from the available set of process data to highlight within the HMI, ending in a FMC demonstrator design. Especially, the HMI design allows the skilled employees to be focused on the process while not having to deal with controlling the automation (robotic manipulator) on a sophisticated level with e.g. teach pendant. From the analysis of the handcrafting process, the spatial environment that skilled employees are used to is mapped to a representative spatial model incorporating newly introduced process quality measures and combining direct manipulation with WYSIWYG interaction approaches. The performed initial user evaluation let to promising results with respect to the developed marker-based interaction technique.

6.3 Future work

Scope of the developed demonstrator is showing and proofing the feasibility of the automation of manual processes that are skill- and experience-based. From the technical perspective, the provided experiments and obtained results show general applicability to the underlying no-bake molding process.

In order to further validate that the proposed, model-based process guiding approach is successful, the presented work may be extended and be applied to comparable HAS. In order to establish the proposed method as common practice for semi-automating manual processes, further application examples need to be selected. From the perspective of the obtained results, a wide field of potential applications can be found in

- assembly lines,

- agriculture domain (e.g. harvesting), or
- surgery domain.

Especially in the domain of surgery, also mandatory legal questions of sharing responsibility and reliability need to be answered.

Labor psychology is a discipline that need to be considered prior to shifting the FMC to the manufacturing line. Thus, questions of how human individuals will deal with the new manufacturing system, how an industry robot is accepted, and also questions of trusting in the FMC safety is an open point that will need further investigation.

Continuing the useware design process and promoting the proposed demonstrator into a standard machining tool is also an open point that is initially performed and introduced by this thesis, but not finalized.

From a process perspective, the gained repetition quality can be used to investigate influence of the recipe on the mold rigidity and the cast parts quality. The detailed analysis and evaluation of compaction quality, recipe, and pattern geometry will lead to an approach of tailored casting, using only chemicals and energy where needed.

Rebuilding concerns can be traced back to the spatial compaction distribution that can be saved as meta-data to each cast part that is flowing through the production sequence. Furthermore, the history of each cast part can be saved and traced back. This feature of gained process feedback can be used to determine e.g. causes of parts malfunction.

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Pre-publications and conference contributions

The thesis is based on the results and development steps published in the following publications and/or presented on the corresponding conferences.

Fu, X., Langer, M., and Soffker, D. (2013). *Toward a modeling of human-centered, rule-based cooperative teamwork*. In: *2013 IEEE 17th International Conference on Computer Supported Cooperative Work in Design (CSCWD)*, pp. 471 –476.

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– (2014). *Event-discrete formal representation of a semi-automated manufacturing process as framework for human guidance and assistance concepts: analysis and application*. In: *International Journal of Production Research* (online availabe, paper version in press), pp. 1 –21.

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Student theses

In the context of the research projects at the Chair of Dynamics and Control the following student theses have been supervised by Dipl.-Ing. Marcel Langer, M.Sc. (USA) and Univ.-Prof. Dr.-Ing. Dirk Söffker. Development steps and results of the research projects and the student theses are integrated to each other and hence are also part of this thesis.

He, C. (2010). *HMI: Das Touchpanel als innovativ-intuitive Schnittstelle zwischen Fertigungsprozess und Fachkraft.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Langer, M. (2011). *Erfassung und Reduktion von 3D Punktewolken zur effizienten Darstellung von gerenderten Oberflächen.* Diplomarbeit. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Ma, X. (2011). *Control of the Impulse Energy Emission of a Compression Tool Based on Experimental Characteristic Diagrams.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Maggoutas, P. (2011). *Path Planning for Manipulators Performing Measurement and Compression Tasks.* Master thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

RahimiFetrati, S. (2010). *Design and Implementation of Instrument VIs for Navigation and Selection Tasks on a Touchscreen using NI LabView.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Rehder, T. (2012). *Entwicklung und Implementierung eines situationsbasierten Assistenzsystems zur Benutzerführung bei komplexen Prozessen.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

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Schmidt, R. M. (2013). *Analyse und Klassifizierung von Oberflächen basierend auf optischen Messdaten.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Severin, T. (2012). *Interfacing Low-Level Information of an Industry Robot for Real-Time-Communication.* Diplomarbeit. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Wolff, S. (2012). *Entwicklung eines 3D-Objekt-basierten Assistenzsystems zur Prozessführung.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Xu, D. (2011). *Action Space-based Attraction of User Attention for Purposes of Process Control.* Master thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Yang, J. (2012). *Modeling Techniques for Human-Process-Interaction.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

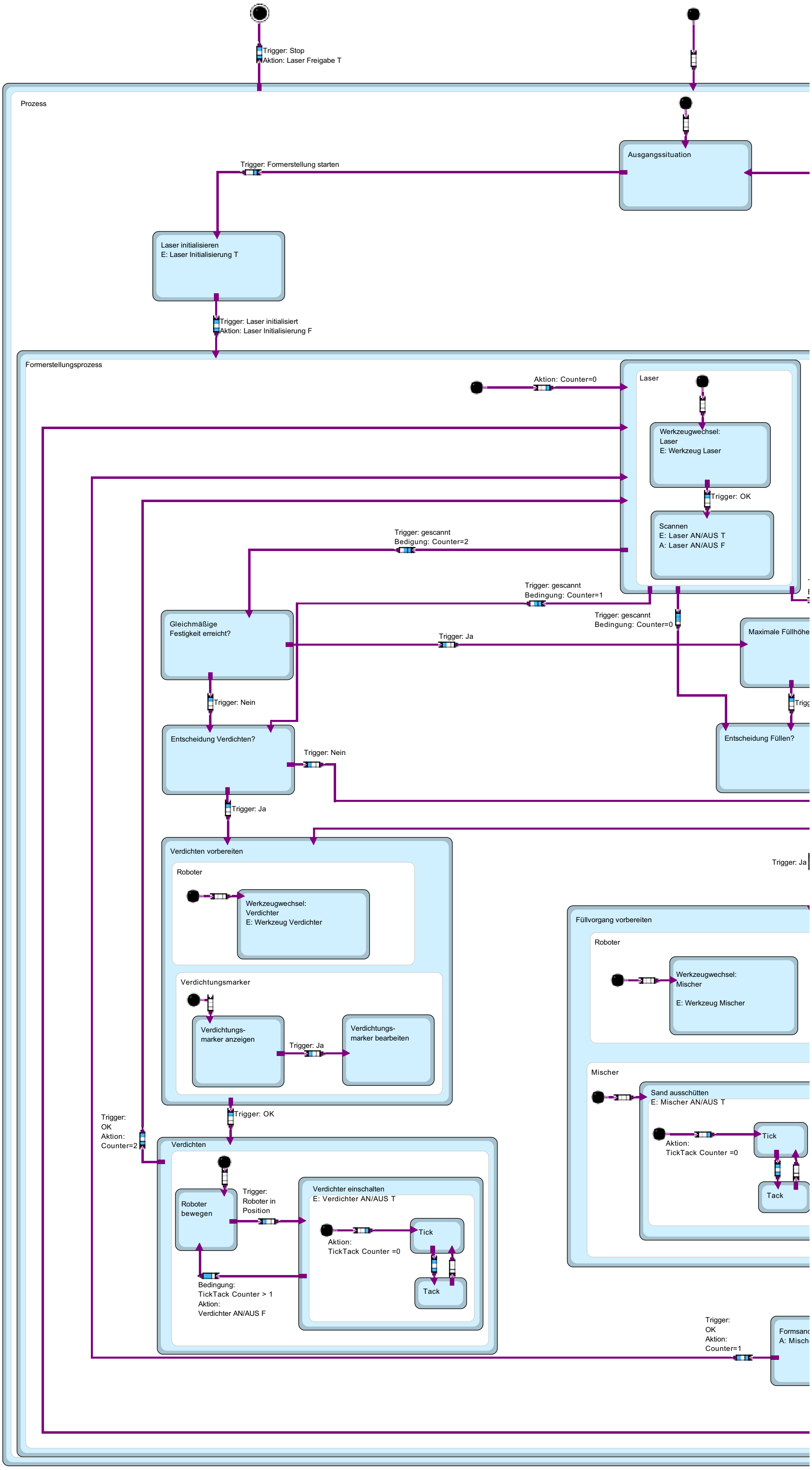
Yu, Y. (2013). *Analysis and Error Management of a Semi-automated Manufacturing System.* Bachelor thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Zhao, B. (2010). *Aufbau und Inbetriebnahme eines Versuchsstandes zur automatisierten Bestimmung des Steifigkeitsverhaltens von Sand.* Studienarbeit. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

Zhong, Q. (2012). *Development and Analysis of a Simulation Model for Sand Compression.* Master thesis. University of Duisburg-Essen, Chair of Dynamics and Control (SRS).

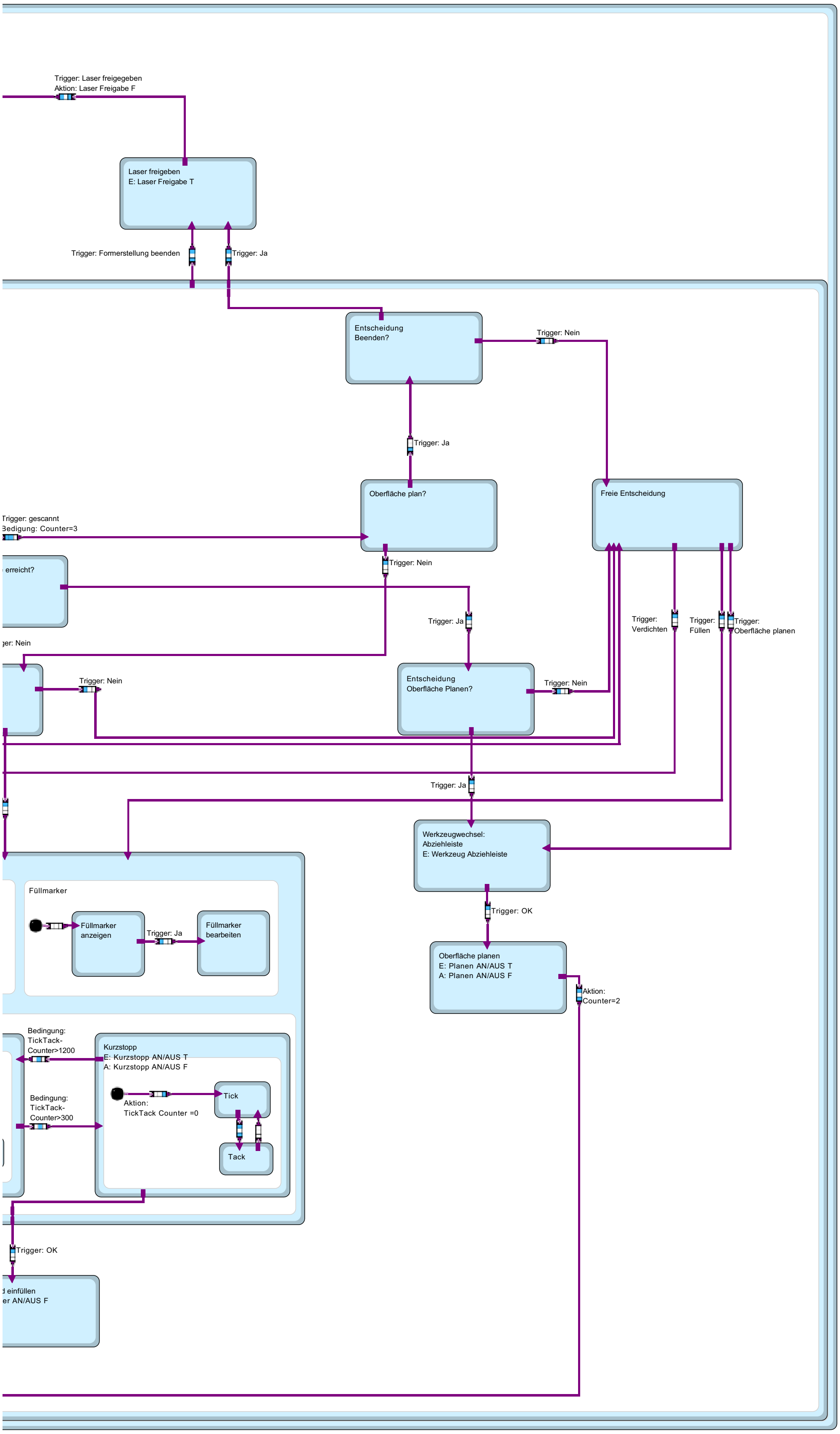
Appendix A

Statechart diagram of no-bake molding



(a) Left part of statechart diagram

Figure A.1 – Statecharts representation of the no-bake molding process



(a) right part of statechart diagram

– continued.

Appendix B

Control application

The control implementation is visualized in Fig. B.1. During the Initialization, the equipment is prepared for operation and corresponding memory is allocated. As soon as all the equipment is signalizing its status to be ready, the HMI is highlighting the status correspondingly on the display. Details on the HMI are given in Section 4.4.4.

The user interaction is noticed by an event-environment, capturing events and triggering meta-operators. The collection of all events will form the desired FMC situation (S_{des}) that is forwarded to the application on human operator confirmation. The Action implementation is taking the desired situation and is translating desired inputs to equipment commands (e.g. Laser on/off) during action pre-processing. Equipment commands are forwarded to physical actions by the corresponding physical interface (e.g. TCP/IP) during the physical implementation. While physical actions are performed, sensor information are captured and collected to form the "real" FMC situation (S_{meas}). If all actions are finished, situation capturing and visualization post-processing is translating sensor information to HAI objects, which are feedback to the human operator.

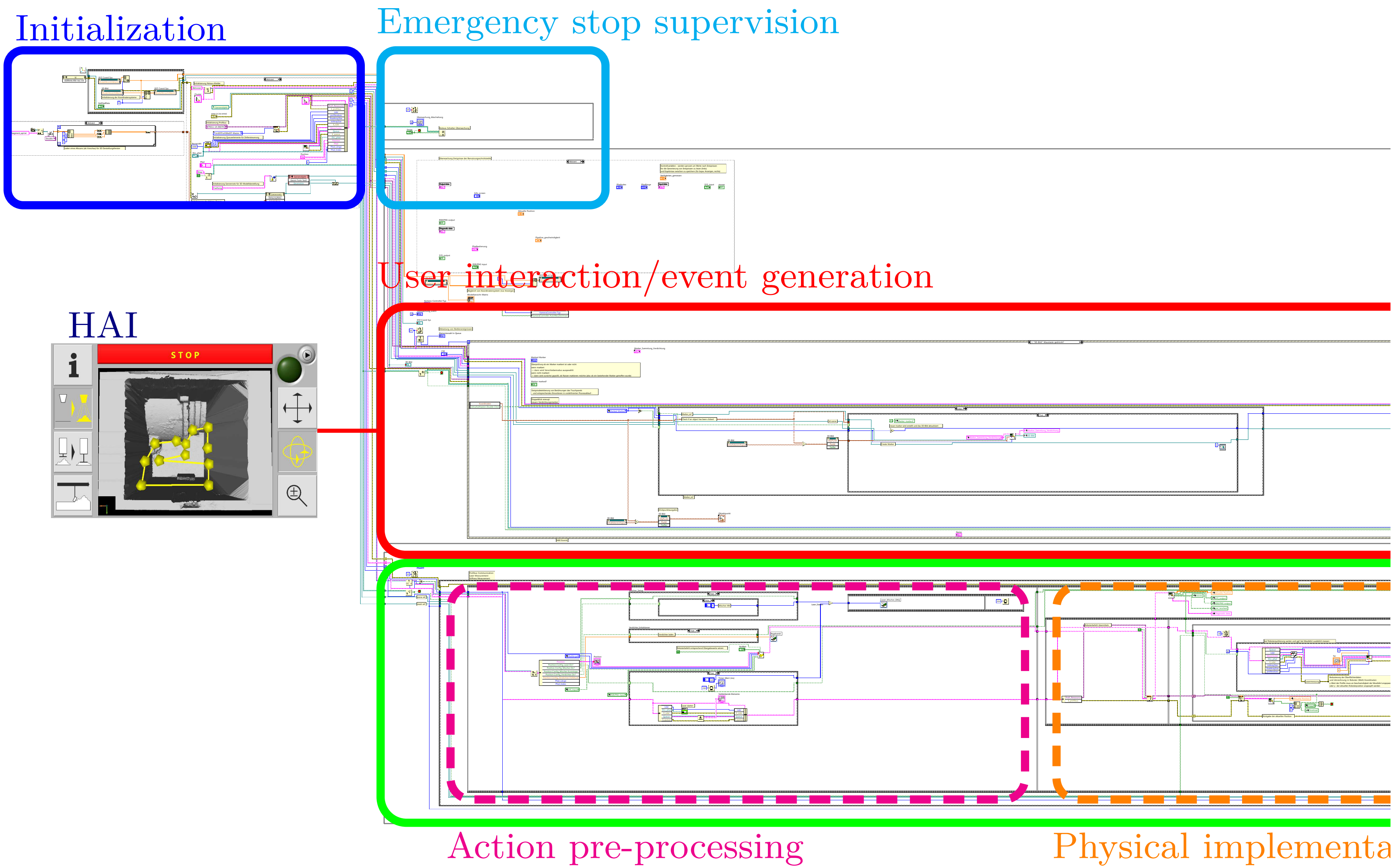
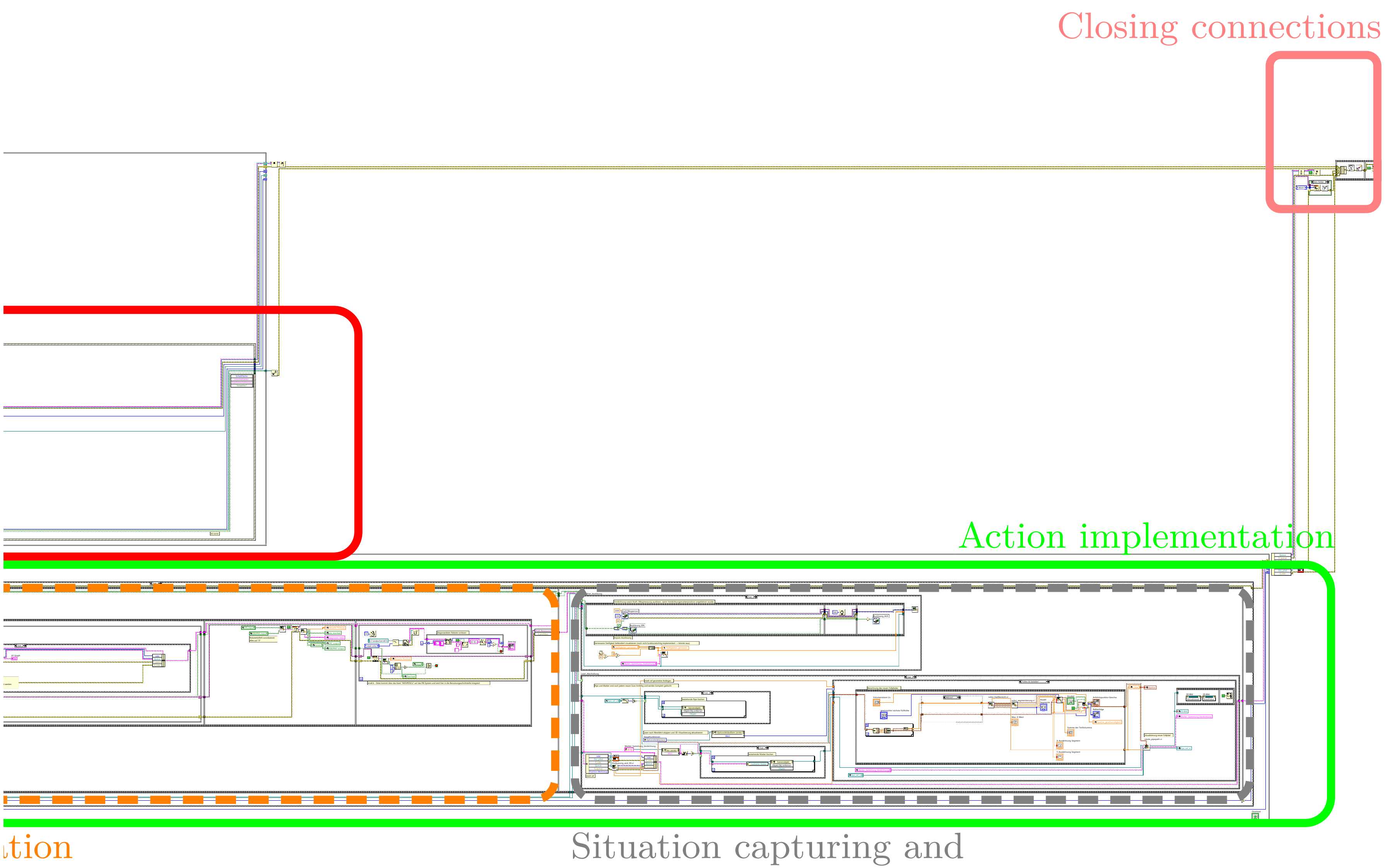


Figure B.1 – Implemented control application based on NI LabView


Closing connections
Action implementation
tion
Situation capturing and

–continued.