Cognitive Challenges of Changeability: Multi-Level Flexibility for Operating a Modular Chemical Plant

Romy Müller[1] and Leon Urbas[2,*]

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Dedicated to Prof. Dr.-Ing. Günter Wozny on the occasion of his 70th birthday

In changeable modular plants, the goal conflicts implied in adjusting the plant to current demands call for flexible strategy selection by operators on three levels: intervention, decision making, and cognitive meta-control. The first level refers to making appropriate changes to the system. This requires flexibility on the second level. Flexibility in operators' choice of intervention and decision strategies depends on the third level, which enables a balance between stability and flexibility. The challenges resulting from these flexibility requirements are discussed by reviewing the literature on adaptive decision making and action control in volatile environments.

Keywords: Changeability, Decision strategies, Modular plants, Stability-flexibility balance

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1 Introduction

Imagine the modular chemical plant BP-117. Its design is optimized for being adjustable to the volatility of the chemical specialties market while producing in a resource-efficient and sustainable manner. To meet these conflicting goals, the plant is set up from autonomous modules – fully automated processing units that can be combined almost as easily as LEGO® blocks [1]. Modular chemical plants are a specific type of cyber-physical production systems, which are characterized by a combination of real (physical) objects and processes with information processing (virtual) objects and processes via open, partly global, and continuously connected information networks [2]. Several features of these systems, such as their interconnectivity and availability of data, are likely to fundamentally change the work of human operators, shifting their responsibility towards highly context-sensitive and dispositive tasks [3]. A distinctive feature of these systems is their technical flexibility: Depending on current demands or the specific type of product, the production process can be altered, e.g., by having the product communicate what it needs and thereby determine which path it takes through the plant or how it is treated. Sometimes, products can even reconfigure the physical system.

All these autonomous or automatable reconfigurations utilize the inbuilt flexibility of the plant, and no additional planning or investment is necessary. However, the tight fit between the requirements of a chemical process and the physical properties of the equipment calls for changeability [4]. In a modular chemical plant, appropriate modules can be selected and exchanged, depending on several constraints. This can be system-inherent physical or process-related constraints (e.g., module Y can operate only in a specific module setup, e.g., in combination with module Z or only at low temperatures), but also external constraints such as the current feed stock situation or changing market demands and prices. Therefore, deciding about module exchanges is all but straightforward, and conflicting constraints cannot be prioritized easily. For instance, while module Y' was not tested under the high temperatures required for a particular process and thus, may pose a risk for product quality, it is much more efficient than the currently used module Y, and as an important customer has placed an urgent order, it may be worth exchanging Y for Y'. In this kind of situation, operators play a central role in deciding about system changes, and ultimately are held responsible for their outcomes. In consequence, operators' tasks differ from traditional supervisory control [5]: Besides monitoring the process and keeping it within predefined limits despite disturbances, they are actively involved in

[1]Dr. Romy Müller
Technische Universität Dresden, Institute of Psychology III, Chair of Engineering Psychology and Applied Cognitive Research, Zellescher Weg 17, 01069 Dresden, Germany.

[2]Prof. Dr.-Ing. Leon Urbas
leon.urbas@tu-dresden.de
Technische Universität Dresden, Chair of Process Control Systems and Process Systems Engineering Group, Georg-Schumann-Straße 11, 01187 Dresden, Germany.

changing the process system by modifying the module setup. There are cognitive factors that can influence operators in dealing with the changeability, and it is a challenging task to operate such plants. The present article examines these factors and tasks before the background of empirical research in cognitive psychology on adaptive decision making and action control.

2 Cognitive Challenges and Multi-Level Flexibility

In modular plants, flexibility is required on three interacting levels. At the core, there is the need for flexible selection of decision strategies: Operators have to find ways of assessing, weighing, and evaluating different decision alternatives and their attributes. How they do this is determined by the two other levels. First, decision strategies are constrained by the specific alternatives for intervention strategies that are available in a given situation. For instance, it will depend on the type and size of the trade-offs between alternatives how exhaustively their attributes must be considered or whether it is okay to selectively focus on a subset of them and simply go for the more convenient alternative. Second, decision strategies are modulated by the broader meta-control strategies that determine whether operators will be more stable and reuse what has worked well in the past, or whether they will be more flexible and tailor their decision making and action selection to the specifics of the current situation.

2.1 Flexible Intervention Strategies: Adapting or Exchanging

In the modular chemical plant BP-117, an operator supervises three production lines. Two of them run quite nicely but the third one consumes way too much energy. In the company's knowledge base, the operator finds no information about this particular combination of modules. However, there is some information about the single modules. High energy consumption tends to occur whenever the reactor module Y is combined with a distillation module Z. To solve this problem, another plant has replaced module Y with Y'. Instead, the module vendor provides specific recommendations for adapting the operation regime of Y modules in order to optimize their performance. This means that the operator is faced with two alternatives: exchanging module Y for Y', or keeping module Y but adapting its parameters (Fig. 1a). The decision is hard as it depends on several characteristics of the process, product, and context. The operator knows that exchanging is clearly superior in terms of its probability for success: It has a high chance of permanently solving the problem, while adapting would merely mitigate it. Moreover, a what-if-analysis with an energy price forecast informs the operator that exchanging would result in a cumulated net value of G, while adapting would gain only half of that. However, despite these benefits, exchanging has some serious shortcomings. First, the time required for exchanging is 60 min, while adapting only takes three. The batch is scheduled to run for another two weeks. Had it been only two days or less, the operator would have had a clear indication to prefer adaptation. Second, the two alternatives have different impacts on product quality, and these impacts are only partly known. A research in the database tells the operator that a Y' module was used successfully in another plant with similar products, but the parameters used there were different: The module only had half the agitator speed, and the operator has no idea whether agitator speed is an important moderator of product quality. If yes, exchanging might reduce energy consumption but ruin the product. The current product is quite sensitive and reacts to tiny changes in temperature, pressure, and educts from different vendors. Therefore, the operator decides to stay on the safe side and not to exchange the module but only to adapt its parameters.

2.1.1 Cognitive Requirements of Selecting Between Intervention Strategies

Adapting and exchanging imply different levels of operator control. When adapting parameters, operators stay within the current way of running a process, merely adjusting its details. Adapting leaves the plant's structure and mode of functioning unchanged and thus, can be considered a less drastic intervention or a more conservative alternative. However, a danger is that for the sake of constancy, process optimization is compromised. In contrast, exchanging implies more fundamental changes. It requires deviating from the current way of running a process in order to optimize the plant for current demands. The physical setup is flexibly adjusted to attain certain production goals. In that sense, exchanging can be considered a higher level control strategy: Variable means are used to make sure that desired ends are reached. Operators' choice between low versus high level control strategies in process control was studied in the context of controlling a thermal-hydraulic process [6]: Some operators' control actions were based on low level constraints. These operators used the same set of physical components in a context-independent way, relied on rote recipes, and performed fixed sequences of control actions with specific devices. Instead, others controlled the system based on process functions (e.g., keeping mass balance constant), using any physical component that might serve to meet this purpose. Such high level control allows for adaptations to novelty and change, because operators can flexibly vary the specific means to achieve desired ends.

It is important to note that when referring to module exchanging as a higher level, more goal-focused means of control than adapting, one does not speak about any specific exchange decision. Of course, in a specific situation adapting may be the perfect way of reaching a goal, so neither strategy is superior in general. Depending on the process state, a production goal can be reached more or less effectively by either adapting or exchanging (Fig. 1b), and in many situations both strategies will be possible. Thus, the notion of exchanging as high level control only refers to operators' general willingness to exchange modules when it is beneficial – being flexible in the low level physical means and focusing on desired ends instead.

However, as discussed in the remainder of this article, a simplified view of desired ends or goals as the determinant of adapt-exchange decisions is problematic. First, in most situations there are several production goals to be met, and they can conflict with each other. Therefore, the optimal cutoff for exchanging will be different for different goals. For instance, to increase productivity it may be beneficial to exchange early, while considerations of product quality may caution against exchanges and suggest making them only when adapting really is not an option anymore, e.g., due to extreme process states. With each goal having its own optimal cutoff for exchanging, operator decisions need to face a number of goal conflicts and make trade-offs between them. Furthermore, besides their implications for production goals, adapt-exchange decisions can exert even more direct impacts on operators. As modules differ in their ease of use, module exchanges can go along with changes in the cognitive requirements of running the process – reducing, amplifying, or merely altering them. For instance, imagine operators working with a filter module Y. Periodically, its continuous operation needs to be interrupted to clean the filter, while the product is buffered in a decoupling tank. Therefore, operators need to ensure that the buffer is almost empty before filter cleaning can start. To do this, they must observe the differential pressure as an indicator for filter clogging, and adjust the flow through the filter so that the buffer does not run completely empty (as this would damage the pumps) but is almost empty so that filter cleaning can start. Therefore, working with module Y makes it necessary to calculate filter cleaning times, which is cognitively costly. Instead, a different filter module Y' can provide significant reductions in workload, because it is equipped with two parallel filters and therefore can run continuously, making the effortful procedures obsolete. To complicate things even more, such cognitive requirements of modules can interact with their technical performance. For instance, while a module might be technically inferior, it can demand fewer mental computations, which in turn may indirectly benefit the production process.

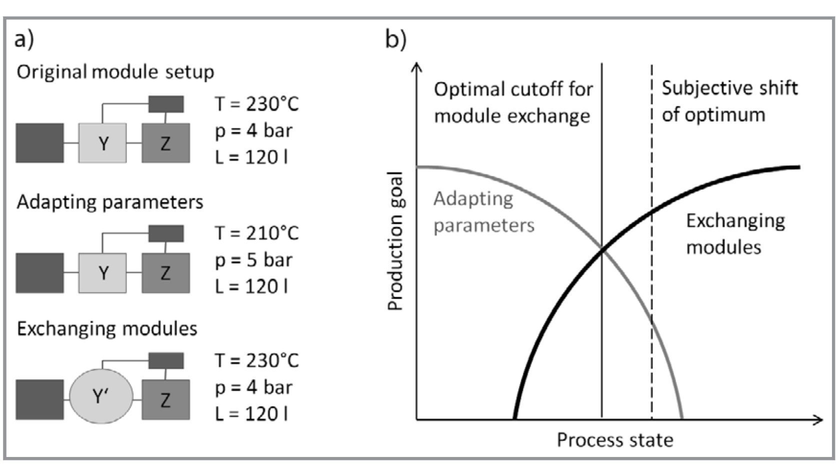


Figure 1. Adapting parameters or exchanging modules (a), and their dependence on the process state and production goals (b). The optimal cutoff can undergo subjective shifts, for instance as a consequence of cognitive biases.

2.2 Flexible Meta-Control Strategies: The Dynamic Balance Between Stability and Flexibility

2.2.1 Goal Conflicts in Decision Making and Action Control

In modular plants, goal conflicts come in two types: that of the plant's production goals and that of operators' cognitive processing when selecting appropriate strategies and actions. The former was discussed in the previous section, and becomes apparent, e.g., when the risks for product quality implied by a module exchange have to be weighed against its benefits in terms of higher efficiency. As a consequence, goal conflicts of the second type arise. For instance, operators can keep on using the strategy that worked well in the past or change it to try a risky alternative. They can go for solutions that are good enough or try to find the best possible one. These two types of goal conflicts mutually constrain each other, because conflict in production goals influences where operators set their thresholds for activities such as exploration of different alternatives or flexible strategy adaptation.

The difficult thing about this is that there is no optimal way of making such decisions. For example, the goal conflicts implicated in coming up with complex strategies need to be considered [7]. When encountering problems in the production process, the question arises how flexibly operators should adapt their decision strategies to the specifics of the current situation. On the one hand, they could generate strategies based on an explicit, rational analysis of the task demands, resources, and other features, constructing a suitable hierarchy of subgoals, and then satisfying each subgoal in turn. The advantage is that they will end up with a special-purpose strategy that perfectly fits the situation, but at the cost of being resource-demanding and slow. On the other hand, operators could simply reuse existing strategies without any adaptation. This is quick and easy but only works if the situation does not differ from previous ones, or if standard solutions can be applied to novel situations.

In between these two extremes, there are all kinds of intermediates, such as switching subgoals based on current demands, or reusing an old strategy but assigning different weights to the subgoals. Goal conflicts arise because an optimal mechanism should generate strategies that satisfy the following criteria [7]: (1) precisely matching the demands of the current situation, (2) avoiding actions that fall out of the domain's constraints (e.g., impossible, illegal), (3) being minimally resource-demanding, (4) persistently pursuing long-term goals, (5) enabling quick adjustments to changes in the environment, and (6) being applicable in novel situations. Obviously, many of these demands are mutually exclusive. Thus, there is no optimal balance between flexible adaptation and stable reuse of pre-existing strategies.

2.2.2 The Stability-Flexibility Balance

Given this absence of an optimum, there are different possibilities for people to balance stability and flexibility. Understanding these mechanisms would be helpful in anticipating in which situations operators will tend towards flexible adaptation to current demands, opt for more stability, or even fall victim to rigidity. Trade-offs between stability and flexibility depend on cognitive control. In general, cognitive control can be understood as a diverse set of mechanisms used by humans to adapt their behavior in ways that allow them to reach goals, maintain goals in spite of distractions, and refrain from reflexively acting on strong response tendencies [8]. The appropriate level of control depends on the current goals and tasks [9]. For instance, when irrelevant information needs to be filtered, a highly selective processing is beneficial. In modular plants, this may be the case when it is important to focus only on module parameters relevant for a given adapt-exchange decision, while not being distracted by all the additional parameters and functions of a module that have no bearing on the current decision. However, while such selectivity and focus improve rule-based and goal-directed decisions, they also impede learning [9 – 11]. Operators who are efficient at ignoring most of a module's parameters to focus only on the currently most important ones may get into trouble if later the ignored parameters become relevant, e.g., when a new product requires a special treatment.

Therefore, goal-directed action is a multiple constraint satisfaction process that aims for a dynamic balance between stability and flexibility [8, 12]. The notion of this balance as being dynamic is essential to understanding the cognitive challenges of modular plants. This is because the plant an operator works in today will only partly be comparable to the one from yesterday, making it necessary to update knowledge, decision strategies, and actions. At the same time, it would be inefficient to start from zero each time a module is exchanged, especially in case of minor changes with circumscribed effects. Thus, trade-offs between stability and flexibility are needed. Tab. 1 lists the trade-offs most relevant for decision making and strategy selection in modular plants, some of which will be discussed in more detail in the following sections.

Various factors determine how operators balance stability and flexibility. For one, this will depend on characteristics of the operator. For instance, expertise can enhance cognitive flexibility [13], and mental states such as confidence and motivation will influence how operators select between staying within the current strategy versus flexibly switching, adjusting, and learning. Moreover, the balance will be modulated by external factors such as performance-contingent reward [14]. However, the current review is mostly concerned with characteristics of the situation and task.

A major situational determinant of the stability-flexibility balance is the volatility of the environment [15]. Volatility modulates the relative influence of recent and remote experiences (e.g., a module's poor performance in the last two hours relative to its outstanding performance throughout the last month). Discounting past outcomes and focusing only on the most recent ones was traditionally coined as a bias in decision research, because it is better to draw from a larger pool of samples. However, temporal discounting is quite sensible when the environment is unstable and thus, recent experiences in fact are more informative [16]. Consequently, in environments that stay fairly constant, people adapt by aligning their behavior with long-term learning experiences, and thus, are less flexible and less influenced by current changes. In contrast, in more variable environments things that worked well in the past may be outdated now, and thus, recent experiences are assigned more weight, making people more likely to adapt to current changes.

Table 1. Trade-offs between stability and flexibility in decision making.

Stability	Flexibility
Applying strategies that were successful in the past	Trying new strategies or re-trying previously inferior ones
Sticking to currently used strategies	Adaptively changing plans and procedures
Re-using previous strategies from other contexts	Developing special-purpose strategies tailored to the problem at hand
Striving for solutions that are good enough	Finding the optimal solution for the current situation
Using quick fixes that are helpful right now	Using solutions that are beneficial in the long run
Evaluating consistently, according to the same criteria	Changing evaluation criteria between situations

Accordingly, higher volatility in a choice environment was found to make people engage in more exploratory behavior [17]. The second important determinant of the stability-flexibility balance is the presence of conflict. In the context of this article, conflict refers to the degree to which different alternatives compete for selection. When conflict is experienced, people mobilize cognitive resources [18], increasing their attention to relevant features of the situation and shielding their goals against distraction. Of course, in modular plants there are many other factors besides volatility and conflict that can affect the stability-flexibility balance, such as the available information on process states, the salience of outcomes, or situational factors such as time pressure. Some of these factors will be discussed in the following sections.

2.3 Flexible Decision Strategies: Choosing Alternatives and Adapting Decision Processes

To understand the challenges of flexible problem solving and adaptive strategy selection in dynamic environments such as modular plants, imagine the following situation: During the production of the very sensitive chemical A, module Y' should only be used when parameter X is x, because otherwise product quality will be at stake. This implies that when parameter X is y or z, it is advisable to use module Y, as it is much safer. However, the situation completely changes when producing chemical B or C. For these products, module Y should be used as much as possible (i.e., when parameter X is x, or y, or z), because this module is inherently easier to use than Y': It requires fewer control actions, less checking of parameters, and less knowledge of its internal functioning. In consequence, while sticking to the simple heuristic of use module Y' when parameter X is x would alleviate operators from the effort of analyzing the situation and differentiating between different process sates, such a heuristic would not result in optimal, context-adaptive decisions. Therefore, we need to understand under what conditions operators are likely to engage in flexible decision-making, adapting their choices and strategies to the requirements of the situation.

2.3.1 Cognitive Flexibility in Decision-Making

The question arises whether people adjust their decision-making to the environment and the situation. As it is often the case in the psychological literature, the answer is that it depends. While some studies provide evidence for decision makers' ability to adapt to changing environments, there is a bulk of research that highlights the limits of this flexibility. First a brief overview of the literature is presented before outlining the boundary conditions for cognitive flexibility.

Early research on adaptive decision making suggests that people can flexibly adjust their decision strategies to different contexts and task demands [19, 20]. Decision strategies differ in how exhaustively they consider the available alternatives and their attributes. An alternative refers to one of several choice options (e.g., module Y or Y', adapting or exchanging), while an attribute is a feature that characterizes these alternatives (e.g., energy consumption of a module, effect of exchanging on product quality). Decision strategies differ in their effort and accuracy. For instance, a strategy high in effort and accuracy is to consider all attributes of each alternative, weigh them, and then choose the alternative that performs best overall. In contrast, a strategy low in effort but also in accuracy is to determine the most important attribute and then simply select the alternative that performs best on this attribute. For instance, if product quality is considered most important, the alternative is selected that is likely to result in the highest quality, regardless of all other attributes such as costs or safety. There is a large number of possible decision strategies and no single one does well under all task and context conditions [19]. Accordingly, adaptivity means that people switch between different strategies depending on situational constraints. In the context of modular plants, a nonadaptive decision strategy is to always prioritize product quality and pay less attention to the time required for a production run when deciding between module Y and Y'. Instead, adaptivity could mean to prioritize product quality instead of time as long as there is no urgent order, but consider both attributes equally when a customer needs the product quickly. Such adaptation is exactly what people do [19, 20]: They are sensitive to characteristics of the situation such as time pressure that make different strategies more or less suitable, and adjust which strategies they use accordingly. On the other hand, ample evidence suggests that flexibility in decision making is quite limited. Such inflexibility comes in two forms, perseveration on chosen alternatives and avoidance of switches between problem solving strategies.

2.3.1.1 Perseveration on Chosen Alternatives

People continue choosing the alternatives that they have chosen in the past [21, 22], which is usually referred to as inertia or routines. In this context, routines are defined as "a behavioral option that comes to mind as a solution when the decision maker is confronted with a certain decision problem." [23]. Such routines can influence all stages of decision processes [24], such as the identification of the problem [25], the search for information [26], the evaluation of attributes and the application of decision rules [27], as well as the actual implementation of behavior [28]. Notably, routines can guide behavior when they are not beneficial or even harmful, and sometimes they are applied even when they have become obsolete and newer evidence speaks against them [27]. In modular plants, this could mean that after a change in the module setup, operators need to experience several times that a previously successful strategy of solving product quality problems by lowering temperature now fails more often than it succeeds. However, of course routines are not followed blindly in every situation, and their application depends on several characteristics of the routines, the environment, and the decision maker. For instance, routines influence decisions more strongly when they were performed more often in the past [27] or when there is time pressure [23], but less strongly when the situation or task is perceived as novel [23].

Decision routines are useful when situational constraints remain constant, but lead to suboptimal decisions when the situation changes. This is of utmost importance for adapt-exchange decisions in modular plants, because the consequences of such decisions will depend on the current production context in terms of the products, recipes, and physical plant setup. People are slow in adapting to changes in the outcomes of decision alternatives [16]. They are quite good at initially adjusting their choices to new decision problems, quickly finding out which alternatives work best. For instance, it will not be hard to learn that a new module Y' does a much better job than the old Y. However, people run into problems when the outcomes subsequently change over time as beliefs are updated rather slowly. When new products with new characteristics are introduced, the old module Y that did worse than Y' a few weeks ago may now have become the better alternative. Often, there is no obvious cue in the environment that signals such changes – no information from the module vendor states that module Y' only works well for products with characteristics E and F but not G. Instead, operators have to deduce this from experience. Such inferences get harder and stickiness increases the longer an alternative has produced good outcomes [16]. Moreover, the speed of adaptation depends on the direction of change [29]: Whereas people adapt quickly when a previously good alternative produces worse outcomes over time, they adapt slowly when an inferior alternative later starts to improve. This is because in the latter case, people often do not notice the improvement as they have started refraining from selecting the alternative early on, opting for exploitation of what currently works, at the cost of exploration. This is critical in modular plants as it could hamper the acceptance of new modules when they produce unsatisfactory outcomes initially, for instance because operators do not know yet how to optimally adjust an individual modules' operation to the overall module setup. As a consequence, operators may refrain from using new modules, which keeps them from learning about their benefits.

2.3.1.2 Avoiding Strategy Changes

The second form of inflexibility in decision making is perseveration on solution strategies. Problem solvers are susceptible to rigidity, being unable to represent problems or perform actions in new ways. The research on this dates back to the discovery of set effects in the middle of the 20th century [30]. In these studies, people typically learn how to solve a problem by using a multi-step procedure. After some trials, they receive a problem that can be solved by using the learned strategy, but also allows for a much simpler solution. Still, people stick to the old, more complicated strategy. If it always worked to exchange module Y for Y' in case of a problem with energy efficiency, operators might do the same now, even when other module changes that were made in the plant would make it sufficient to simply adjust a parameter of Y. Perseveration on strategies cannot only be observed in the way people perform specific steps to solve problems but also in the way they search and integrate information about different alternatives [31]: When in a stock market game the payoff structure changed after several trials, participants nevertheless stuck to their old (although now suboptimal) strategy of obtaining information about different alternatives. In modular plants, this could mean that when in module setup Y it was necessary to check pressure, temperature, level and inflow ratio to decide whether flow rate can be increased or a module needs to be exchanged, operators might continue to do this in module setup Y' even when due to its different properties it would be sufficient to only check temperature.

Such perseveration even occurs when people are well aware of the different strategies. Ideally, they should select the most appropriate strategies, those that lead to better outcomes or are easier to use. But instead of making such comparisons, people often prefer to reuse previous strategies rather than switching them [32], presumably because using a strategy increases its activation in memory, and thus, its availability, eliminating the need for effortful mental reconfiguration. Usually, the effects of strategy reuse reported in the literature tend to be small when the choice has real consequences for subsequent work: If the task makes a particular strategy more easy to use than the other, the repetition bias disappears [33]. However, other studies report that people avoid strategy switches even when this delays task completion and requires more actions [34]. Future work should investigate the boundary conditions for flexibility versus rigidity in strategy choice.

Taken together, while there is some evidence for flexible adaptation of strategies, most studies emphasize the limits of this flexibility, and instead show that decision makers are susceptible to rigidity. And in fact, it makes sense that people stick to routine choices. After all, having a strong routine means that you can rely on a large pool of prior experiences, and thus, sticking to routines means that people are not guilty of base rate neglect [27]. Strong routines should make people more reluctant to deviate from them, because it means that again and again these routines have done a good job. Similarly, it makes sense for people to avoid strategy switching, because it is cognitively more costly and can degrade performance: People perform worse when they use different strategies to repeatedly solve similar problems than when they keep using the same strategy [32]. If operators exchange a module and as a consequence they must perform different mental computations while supervising and controlling it, the cognitive costs of this exchange might outweigh the benefits of the module's higher capacity, leading to inferior performance of the overall system. Thus, routines certainly have their merits and can massively reduce processing demands. On the other hand, continuing to use the same strategy only is a good option when the environment does not change. As such change is just what characterizes modular plants, the tendency for perseveration is likely to be a problem in these systems, keeping operators from using their full potential.

2.3.2 Influences of the Situation: Complexity and Conflict

Cognitive flexibility in decision making is influenced by situational factors. For instance, the complexity of decisions determines how people choose between alternatives. Such complexity can arise from different factors: Decisions get harder if there are more alternatives, more attributes that describe the alternatives, or more information about the alternatives and attributes. Critically, decision complexity often leads people to use simpler decision strategies. For instance, they might eliminate some alternatives immediately, or engage in more shallow and selective information search [35]: In a study that systematically varied the number of alternatives and attributes in decisions about job candidates, these numbers affected the selection and use of information as well as the decision rules applied by participants. Most notably, when more alternatives were present, the number of judgments per alternative was lower and people more readily used elimination strategies (i.e., quickly throwing out alternatives). Similar findings were obtained in the context of consumer choices where a higher variety of available products to choose from can lead people to refrain from exploring the alternatives [36]. For modular plants this could imply that when operators are faced with many alternatives of exchanging modules and adapting parameters, they might restrict their focus to only a few of them, and potentially ignore alternatives and attributes that are worth considering.

The mere availability of alternatives can increase the computational demands of decisions and produce conflict as decision makers do not know how to trade off various costs. However, conflict also critically depends on type of alternatives and attributes, and it arises whenever the trade-offs between decision alternatives are hard [37]. Trade-offs get hard when different alternatives are similarly attractive [38], when some attributes speak for one alternative while others speak for the other [20], or when the trade-offs are higher [37], e.g., when in terms of product quality module Y is much better than module Y' while in terms of energy efficiency it is much worse, compared to being only a bit better and a bit worse. Also, conflict is subjectively higher when the situation requires a decision between alternatives that both are undesirable, compared to a decision between alternatives that both are desirable [39]. For instance, if module Y is broken and you will definitely lose by exchanging it for Y' or Y" so that the question is just in what configuration you are losing less, this is harder than if you get the chance to replace an outdated module Y with either Y' or Y" that will both be better than Y anyway. Finally, conflict increases with higher importance as decision makers are reluctant to make trade-offs on attributes that affect more important goals [40]. If operators consider product quality to be of utmost importance and this quality depends on the filtering process, then they might not be inclined to use a module that has worse filtering quality, even if it has several other benefits.

Given that conflict makes decisions so hard, there are many options for decision makers to deal with them. In principle, different possibilities basically boil down to a choice between facing or avoiding conflict [20]. Facing conflict can be achieved by using all or most of the relevant information and making trade-offs among the good and bad attributes of each alternative, thus, engaging in more effortful decision strategies. In contrast, avoiding conflict is reflected in different shortcuts that simplify the decision problem: ignoring potentially relevant information or refraining from making trade-offs, e.g., by only focusing on the most important attribute and selecting the alternative that performs best on this attribute. Alternatively, avoiding conflict can mean that people refrain from making decisions altogether. In fact, there is evidence for both, facing and avoiding conflict. In terms of facing conflict, it was found that in decision contexts with negative intercorrelations between attributes (i.e., you need to give up something to get something else), people use less heuristics, engage in a more thorough information search, and process information less selectivity [20]. However, several other studies have led to the conclusion that people often avoid conflict, even to a point where conflict and uncertainty can lead people to refrain from making a decision altogether [36, 38, 41]. Instead, they defer, search for new alternatives, or simply select the default alternative. Deferral is most likely when the choice set contains several equally attractive alternatives [38]. This implies that adding alternatives can lead to no choice at all, which is a somewhat alarming message with regard to modular chemical plants. Paradoxically, when all kinds of special-purpose modules are available to choose from, this might keep operators from exchanging modules and instead make them leave the situation as it.

2.3.3 Influences of the Decision Maker: Cognitive Biases

Cognitive flexibility in decision making and the choice between adapting or exchanging modules will also depend on characteristics of the decision maker, and several cognitive biases may have an impact. Most notably, there is the status quo bias [42], which refers to a preference for leaving situations as they are. This bias can at least partly be traced back to loss aversion, the fact that losses subjectively weigh more than gains [43]. In consequence, people are riskaverse when losing something is at stake, and more willing to invest in preventing losses than in increasing gains.

Another important bias with regard to adapt-exchange decisions is effort discounting: People tend to choose actions that minimize demand. This "Law of Less Work" has been known for a long time [44], but typically been investigated in the context of physical effort, where even minimal efforts on the scale of milliseconds can affect action selection [45]. However, the same holds for cognitive effort. For instance, people usually choose cognitively less demanding tasks when given a choice [34], use heuristics or simple rules of thumb as to save mental effort [46], and minimize cognitively straining, knowledge-based processing [47]. Early empirical evidence for reducing mental effort stems from studies on the fault finding strategies of electronics technicians [48]. They traded off mental effort for physical effort, preferring rapid sequences of many small actions and informationally redundant checks to test the state of a device, instead of engaging in careful reasoning about the system's internal functioning, which would have allowed them to identify the most informative tests. In modular plants, physical and cognitive effort often need to be balanced, because the process of exchanging modules obviously requires more physical effort than adaptation, but might be compensated by reductions in cognitive effort following an exchange.

The previous section only focused on effort, but in most situations reducing effort goes along with compromising scrutiny and accuracy. This is referred to as the efficiency-thoroughness-trade-off [49], the conflict between getting things done versus doing things well. In most situations, there is limited time and resources, and therefore such trade-offs are necessary and useful. On the other hand, especially in complex and uncertain situations there are serious risks implied in reducing the time and effort spent on understanding the situation, on choosing and planning, and on performing actions only after checking for possible side effects. Comparable trade-offs are made by decision makers. In principle, you can be anything between a maximizer and a satisficer [50], looking for the very best alternative versus taking the one that is good enough in terms of crossing some threshold of acceptability. The problem with maximizing is that it requires exhaustive search and investigation of all alternatives, leading to severe choice overload. Trade-offs during decision making were described in the effort-accuracy model of strategy selection [19, 20] and investigated extensively: People select decision strategies by trading off costs (effort) and benefits (accuracy) based on situation and task variables (e.g., time pressure) as well as variables related to the particular decision alternatives (e.g., similarity or intercorrelations among the alternatives). An implication for modular plants is that operators may not always try to find the best alternative when deciding about plant configurations but opt for alternatives that are good enough, especially if they need to deal with constraints such as time pressure.

Many other biases in decision making may be relevant for operating modular plants. For instance, as another consequence of loss aversion, decisions are hard when alternatives are unattractive, which can be the case, e.g., when they are all worse than a previously available reference [37]. Adapt-exchange decisions may be hard when operators have to choose between exchanging module Y for Y' and adapting within module Y, while none of these alternatives is really satisfactory because it would be best to use module Y", which is currently being repaired. Moreover, people tend to neglect long-term outcomes. Decisions often make it necessary to find a balance between obtaining immediate benefits vs renouncing them and instead doing what is best in the long run. In modular plants, it may be easier for operators to make a simple parameter adaptation now, but this may mean that they have to spend more effort on supervising the process later, whereas if they had exchanged the module, the problem would have been solved completely. Sometimes, people may not even be aware of such trade-offs, and thus, simply choose the alternatives that they believe to have the largest immediate payoffs, while not considering long-term benefits [17]. However, even when people are explicitly asked to choose between immediate small benefits and a larger delayed ones, they often prefer the small immediate benefits, a phenomenon referred to as delay discounting [51]. This tendency might be exacerbated in modular plants, because less predictable environments should enhance the focus on immediate benefits [52]. After all, one has to make the decision to invest in something that might turn out positively in the distant future, not knowing what that future will be. Still, such discounting can be problematic in modular plants if it results in operators avoiding module exchanges that require immediate effort but result in better long-term outcomes.

3 Discussion

Modular plants are highly changeable systems that allow for changes in the module setup. However, when deciding about whether and when to make such changes, operators are faced with a number of goal conflicts and have to make trade-offs when selecting appropriate intervention strategies. Decision making is not always adaptive and flexible, and people tend to perseverate on choices and avoid strategy changes. This (in)flexibility is modulated by the complexity and conflict inherent in decision situations as well as by a number of cognitive biases. Taken together, there is reason to believe that operators may not take advantage of the full potentials offered by the changeability of modular plants without support.

3.1 Applicability of Psychological Findings in the Real World

The psychological literature provides plenty of insights into the way people deal with changing task contexts. However, modular chemical plants are not a psychology lab and one needs to question to what degree these insights can be transferred to the real world.

One critical issue is whether operators actually make adapt-exchange decisions in the moment when a particular process state occurs. Alternatively, decisions might be more rule-based and memory-driven, relying on the setting of cut-offs and a retrieval of preconfigured responses to environmental cues [25, 53]. That is, operators may have made at least part of the decisions well in advance of the current problem, either based on self-instruction (e.g., if product quality ever falls below value *h*, the reactor module needs to be exchanged) or on a recall of experiences following the recognition of situations (e.g., whenever this problem occurred, adapting parameters worked well). However, in changeable systems such preconfigured responses can be problematic as the meaning of situational cues used for recognition will depend on the current plant context. A parameter value that was critical in a previous module setup may be completely normal in the current one. This variability sets limits for recognition-primed decision making [25], which presupposes that operators can learn about the regularities of the environment [54]. Designers of modular plant concepts might want to limit the degrees of freedom to provide sufficient consistency between situations in modular plants for operators to develop a broad base of experiences to be recalled.

A second critical issue is the role of outcome goals. In a modular plant, operators are required to meet high production standards. Generally, having specific, difficult goals can be highly conducive to performance [55]. However, some characteristics of modular plants closely resemble the boundary conditions at which goals can become detrimental to performance. Difficult, specific outcome goals encourage people to engage in more risky behavior [56]. Moreover, they interfere with the acquisition of knowledge about the task environment, and restrict exploration in complex tasks [57]. They foster the learning of isolated solution paths instead of understanding the problem space by systematically testing hypotheses, which results in impaired transfer of strategic knowledge, e.g., when a different goal state makes it necessary to adjust tools and parameters accordingly [58]. In contrast to outcome goals, learning goals have a more positive impact on performance and strategy selection in complex tasks [59]. These basic psychological findings affect objective economic outcomes as learning goal orientation is associated with higher job performance [60]. This effect is mediated by self-regulation tactics, speaking to the fact that at least in some work settings success depends on the willingness to broaden your skills. Of course it is problematic to freely experiment during the actual production process, but simulation is a promising tool [61, 62]. Moreover, due to a modular plant's continuous real-time connection with its digital twin, it can provide operators with the opportunity to generate forecasts or run what-if analyses.

Third, it should be noted that the cognitive challenges of modular plants like presented in this study stand in sharp contrast to a major theme in current discussions of operator roles in other highly autonomous systems: the challenge of passive cognition [63]: Operators are removed from the task, mostly assuming the role of a passive monitor, which impairs system understanding and situation awareness. For instance, when operators have to take back control in autonomous driving, they encounter difficulties for extended periods of time [64, 65], which also manifests in impaired information acquisition behaviors such as lane checking [66]. However, we do not think that passive cognition poses a comparable challenge in modular plants. In contrast to domains such as driving, operators of chemical plants were interacting with highly automated systems for decades, so monitoring is not a new task. Conversely, in modular plants operators' cognitive involvement may even increase, due to their role in actively reconfiguring the module setup. It will be interesting to study the impacts of modularity on frequently discussed problems of process control such as complacency or vigilance [67, 68].

A challenge that will certainly become relevant in modular plants is learning and transfer, because not only do operators have to decide about changes to the module setup, they also need to cope with changes that have been performed by others, e.g., during a previous shift. System changes can impair performance, especially when previously learned strategies cannot be applied anymore [69, 70]. Accordingly, in order to cope with the changeability of modular plants, operators need to be flexible in mentally representing the system. On the one hand, they must update their understanding of the system. This can necessitate changes in their theoretical concepts [71] and in their understanding of functional relations between system variables [72]. Accordingly, differentiation and situation-specific mental representations are essential, although focusing only on the currently most relevant attributes while ignoring others can reduce conceptual flexibility and impair learning [10]. On the other hand, knowledge must be transferred to situations even when they are not completely identical to previous ones. Transfer is challenging if situations are only similar with regard to their structural and causal relations but not in their surface features [73]. However, transfer can be supported by means of providing diverse learning experiences [74]. In this regard, changeable, and thus, highly diverse modular plants provide a unique potential for ongoing operator qualification.

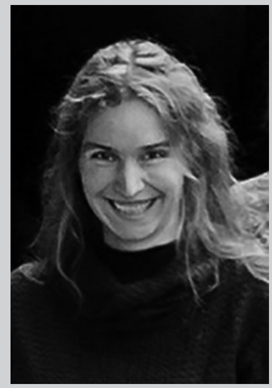
3.2 Interface Design to Support Flexible Problem Solving

Operators can be supported in dealing with the changeability of modular plants, e.g., by means of designing human machine interfaces. Some approaches might be rather straightforward and could directly be inferred from the literature on decision making in changing environments. For instance, it was found that people deviate from their routines more readily and engage in more thorough information acquisition when the situation looks novel [23, 27]. Comparable manipulations could be achieved by techniques as simple as adding a new label, color, or other salient surface feature to a module's interface and thereby making differences visually salient. Moreover, visualizations were proposed that support decision makers in multiple criteria decision making [75]. These tools can aid operators in dealing with goal conflicts as they enable a consideration of several goal dimensions at once (e.g., productivity, product quality, production costs, safety). However, weighing these dimensions remains a problem that can hardly be solved by visualizations as there is no situation-independent way of balancing trade-offs automatically (e.g., it is unclear whether higher costs of processing with module Y' than Y are more important than the higher safety it provides).

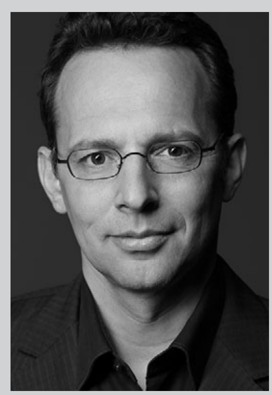
In many respects, it is supposed that suitable strategies for interfacing cyber-physical production systems with human decision makers do not fundamentally need to differ from those developed in the human factors community over the past 30 years, and some suggestions were provided in a recent chapter [76]. For instance, flexible decision making and higher level control can be supported by providing integrated information about plant functions [6]. However, there also are design strategies and guidelines that probably should not be adopted in modular plants. Providing the right information can be tricky when operators need to deal with change, and some interventions that work well in stationary situations cannot simply be applied to changing situations. For instance, providing a history in terms of summary statistics can backfire in volatile environments, where it is adaptive to weigh the recent past more strongly than the distant past [16].

4 Conclusion

In a constantly changing environment that is characterized by goal conflicts, there is not a single best way of selecting and implementing intervention strategies, decision strategies, and cognitive meta-control strategies. Thus, multi-level flexibility is a feature of intelligent, adaptive behavior. Most of the challenges presented in this article will not be specific for humans but would also need to be dealt with by algorithms in autonomous systems. Currently, such algorithms are capable of optimization on the most concrete level of intervention strategies, and mostly operate by applying fixed decision strategies. It is completely out of their scope to be flexible on the level of cognitive meta-control strategies, and thus, finding a dynamic balance between stability and flexibility remains to be an indispensable function of humans. Accordingly, a main focus of research should be the improvement of cooperative decision making between humans and machines in changeable systems. Moreover, irrespective of function allocation and the level of automation, a key success factor for the design of modular plants is to find useful compromises between changeability on the one hand, and keeping the variety of options manageable on the other. In any case, ample potential and challenges for interdisciplinary research will be provided by the cognitive challenges of changeability.



Romy Müller is a PostDoc at the Chair of Engineering Psychology and Applied Cognition of the Technische Universität Dresden. After studying psychology, she was working as a research scientist at the Chairs of Engineering Psychology and Applied Cognition as well as the chair of Media Design of the TU Dresden. In her Ph.D. thesis (2012) she focused on the technical support of remote cooperation by way of transferring information about the partners' visual attention and action to improve interpersonal coordination. Her research is concerned with bridging the gap between basic research on cognitive control processes and applied aspects of cognition and action in human-machine systems.



Leon Urbas directs the Chair of Process Control Systems and the Process Systems Engineering Group at Technische Universität Dresden. He is a computational systems engineer with a Ph.D. on Operator Trainings Systems and several years of industrial experience. In 2000 he gained a 6-years VolkswagenStiftung grant to lead a research group on human performance modelling. He investigates methods for and opportunities of digital transformations in process industries, with a research focus on modular process systems design, the alignment of the life cycles of a real plant and its digital twin, and innovative ways to utilize the real-time integrated network of models, simulations and data to interface human decision makers with chemical plants.

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