

Article

Adapt/Exchange Decisions Depend on Structural and Surface Features: Effects of Solution Costs and Presentation Format

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Abstract: Problem solvers often need to choose between adapting a current solution and exchanging it for a new one. However, previous studies have not considered how such decisions might depend on structural and surface features of the task. Therefore, the present study investigated the interplay between the costs of the two solutions (a structural feature) and the format in which this information is presented (a surface feature). In a computer-based modular plant scenario, participants chose between modifying process parameters (Adapt) and reconfiguring the module setup (Exchange). The solution costs were presented either as graphs depicting parameter relations, separate numbers for each parameter, or integrated numbers for each solution. It was hypothesised that graphs induce satisficing (i.e., basing decisions only on Adapt), whereas the numeric formats foster a comparison of the solutions (i.e., basing decisions on the Adapt/Exchange ratio). The hypothesised effects were restricted to situations with medium Adapt costs. A second experiment replicated these findings while adjusting the scale of the numeric formats. In conclusion, Adapt/Exchange decisions are shaped by an interaction of structural and surface features of the task. These findings contribute to a more detailed understanding of the influences on decision strategies in complex scenarios that require a balance between stability and flexibility.

Keywords: decision making; Adapt/Exchange decisions; satisficing; structural and surface features; costs; presentation format; modular plants



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1. Introduction

The balance between stability and flexibility is a cornerstone of adaptive action control [1,2]. However, human decision-makers can be remarkably inflexible. They tend to go with defaults [3] and try to keep up the status quo [4–6]. However, sometimes changes are inevitable because a previously successful solution does not work anymore. In such situations, what kind of changes do people make? Do they merely adapt the details of the current solution or exchange it for a completely different solution principle? In industrial contexts, the technical innovation of modularity introduces this issue into the daily work of operators, as modular plants enable a flexible reconfiguration of their physical setup [7]. Accordingly, operators can choose between local and global changes [8]. They can either modify process parameters like temperature or pressure within the narrow ranges of the current module (Adapt) or reconfigure the plant and use another module that enables production at more suitable parameter ranges, for instance, because it has a bigger reactor (Exchange). How do people arrive at a decision in such situations?

The cognitive processes underlying Adapt/Exchange decisions are poorly understood. One open question is under what conditions people engage in a thorough comparison of both solutions. Two previous studies suggested that decision-makers often refrain from checking an alternative Exchange solution [9] and base their decisions only on the costs of Adapt, while ignoring the cost ratio of Adapt and Exchange [10]. In other words, they seem to apply a satisficing strategy [11,12]. Satisficing is defined as “using experience to construct an expectation of how good a solution we might reasonably achieve, and halting search as

soon as a solution is reached that meets the expectation" [11], p. 9. While previous research has often understood satisficing as a specific heuristic during sequential choice, e.g., [13], we use the term in a broader sense: considering only a particular solution, as long as it is good enough. This understanding of satisficing aligns with its use in the framework of Naturalistic Decision-Making [14]: when experts solve emergency problems, they go with the first solution that comes to mind, mentally simulate this solution to see whether it can be successful, and directly choose it when this is the case. Usually, no further alternatives are considered.

With regard to satisficing in previous Adapt/Exchange studies [9,10], it is an open question whether participants relied on this strategy because it was suitable given the structural features of the task. Alternatively, surface features might have nudged them into a heuristic type of processing. The former possibility rests on the assumption that simple heuristics like satisficing can lead to good outcomes when they are adjusted to the structure of the environment [15]. One condition under which satisficing greatly supports decisions is when the options are incommensurable [11], either because their large number of attributes cannot be compared or because their outcomes are uncertain. Both factors apply to Adapt/Exchange decisions, particularly in complex industrial settings. This is because the two solutions may not only differ in their explicitly quantified costs (e.g., magnitude of undesirable interference with the production process) but also in other, non-quantified costs (e.g., efforts and risks). Thus, the explicit attributes only represent a fraction of the actual attributes of each solution. These explicit and non-explicit costs represent a structural feature of Adapt/Exchange decisions, which might have induced satisficing in previous studies. Alternatively, satisficing might have resulted from surface features of the task, particularly the format in which the Adapt and Exchange costs were presented. It might just have been too difficult to compare the two solutions principles. If so, people should no longer satisfice when the presentation format facilitates this comparison.

Taken together, we currently do not know whether people satisficed because of the way the costs of the solutions were distributed (i.e., a structural task feature) or because of the way the information was presented (i.e., a surface feature). Understanding the impacts of such context features on Adapt/Exchange decision strategies is important both for theoretical and practical reasons. From a theoretical perspective, it allows us to critically assess which findings from basic decision-making experiments generalise to more complex decision contexts. This can foster a more nuanced understanding of human cognition. From a practical perspective, it would allow us to design more targeted interventions in operator assistance systems and training programmes. Therefore, the present study investigated how structural and surface features of Adapt/Exchange tasks interact in shaping decision strategies. Before specifying the research question and introducing the experimental setting, we will provide a theoretical background on the effects of presentation format in different decision contexts and elaborate on the requirements of Adapt/Exchange decisions in a particular industrial scenario.

2. Theoretical Background

2.1. How Does Presentation Format Affect Decision-Making?

Effects of presentation format have been observed in several decision contexts, two of which are particularly relevant to Adapt/Exchange decisions: intertemporal choice and multi-attribute decision-making. In intertemporal choice or delay discounting, people choose between a sooner/smaller and a larger/later reward and consistently discount rewards as a function of time. That is, rewards lose their subjective value when people have to wait longer to receive them [16,17]. The rate of such discounting varies with presentation format, and two types of format effects have been reported. One depends on the *units of rewards and delays*. In short, people are more willing to wait when the time interval is less transparent or when the amount of reward is more transparent. The time interval can be made less transparent by presenting delays as specific dates rather than numbers of days [18–20]. The rewards can be made more transparent by making them easier to

estimate, for instance, by using familiar units [21]. Both manipulations cause people to be more patient. The second type of presentation format effect relies on a *highlighting of gains and losses*. In short, people are more willing to wait when the consequences of both options are emphasised and clearly differentiated. This can either be achieved by making explicit what is missed when not choosing the larger/later option [22,23] or by emphasising the costs of choosing the sooner/smaller option [24]. Again, both manipulations cause people to be more patient. Taken together, depending on how the options are presented, attention can be guided to different features of the decision (e.g., length of the time interval, magnitude of the delayed reward of the larger/later option, unwanted future consequences of the sooner/smaller option). These differences in attention allocation may change how people decide.

A second decision context in which presentation format influences choice is multi-attribute decision-making. In this setting, people choose between two or more options that differ in their values for a number of shared attributes (e.g., four houses differ in their size, price, quality of the neighbourhood, connection to public transport). People usually do not compare all options on all attributes weighted by their respective relevance or validity but use simpler heuristics [25,26]. Effects of presentation format come in two types. One depends on a *variation of attribute modalities and attribute scales*. In short, the influence of attributes can be increased when they are made easier to comprehend or when they are expanded. Attributes can be made easier to comprehend by supplementing numerical information with explicit quality evaluations [27], by using graphical formats instead of just numbers [27,28], and by expanding the axes of diagrams to make the respective attributes seem more important [29]. Similar expansions can be applied to numbers, for instance, by presenting prices per year instead of per month [30]. All of these manipulations make people put more weight on the respective attributes, increasing their impact on decisions. The second type of presentation format effect depends on the *need for information search*. In short, when the presentation format makes the information less accessible and the comparison of options more difficult, people rely on simple heuristics instead of comparing the options on all attributes in a weighted additive manner. Information accessibility is reduced when people have to go through the attributes sequentially [31] or when a map-like presentation format ties each attribute to a particular location [32]. Both increase the need for information search and lead to simpler, more selective decision strategies. Taken together, how people use attributes depends on whether these attributes are comprehensible and accessible. People are more likely to base their decisions on information that they can easily find, understand, evaluate, and integrate.

Adapt/Exchange decisions are similar to both of the previously discussed decision contexts. For a detailed comparison, see [10]. First, they require choices between a solution that is low in rewards and costs versus one that is high in rewards and costs, making them similar to intertemporal choice. Second, they require assessing and integrating a variety of different features of the two solutions, making them similar to multi-attribute decisions. This raises the possibility that some of the presentation format effects discussed above can also make people less inclined to satisfice and more inclined to compare the Adapt and Exchange solutions. Therefore, in the present study, we aimed to make attribute values more or less easy to estimate and compare, and to facilitate or impair information search.

2.2. Why Do People Satisfice When Making Adapt/Exchange Decisions in Modular Plants?

Consider the following scenario. While producing an expensive chemical, a problem can either be tackled by adapting process parameters (e.g., temperature, pressure) or by exchanging the current reactor module for a more suitable, bigger one. Operators are informed that, if they choose Adapt, they need to substantially increase the temperature in order to still reach the production goals, as the current reactor actually is too small. Since process interventions put the chemical process at risk, you generally want to keep them to a minimum. Instead, much less process intervention is required when choosing Exchange: the bigger reactor of the new module makes it possible to substitute temperature

changes for volume changes, which have no negative side effects. Therefore, Exchange seems preferable according to the available information. However, at the same time, it has costs that are not made explicit: the module exchange requires physical effort, takes time, and can pose its own (partly unknown) risks for the process and plant. These non-explicit costs of Exchange might outweigh the costs of Adapt, especially when the latter only requires minor adjustments. Thus, why would operators invest effort in a module exchange when the production goals can safely be achieved by merely adapting parameters? When the solution achievable via Adapt is already known to be good enough, it simply might not matter how much better Exchange performs on the explicit attributes (e.g., required process intervention).

This could explain why in a previous study [10], no evidence for a thorough comparison of the two solutions was found. Participants went through sequences of Adapt/Exchange decisions with gradually changing cost ratios (i.e., process intervention required for Adapt vs. Exchange). That is, Adapt either became successively better or worse than Exchange. It was also varied whether the gradual cost ratio changes were accompanied by gradual increases in the absolute Adapt costs or whether these absolute costs alternated between trials. Participants' choices did not depend on the gradual increase in the cost ratio but only on the absolute costs of Adapt. Moreover, participants were faster when choosing Adapt than Exchange. These results suggest that Exchange choices involved an additional mental operation (i.e., evaluating the Exchange solution) and that participants skipped this additional effort when choosing Adapt. Apparently, they simply chose Adapt whenever it was good enough. That is, they adopted a satisficing strategy. This might have been a suitable strategy due to the structural features of the Adapt/Exchange decisions. However, it needs to be noted that participants had to base their decisions on a rather complicated graph visualisation, which depicted the costs of the two solutions as relations between process parameters and production goals. This presentation format arguably made the comparison of the solutions rather difficult. As high task difficulty can induce satisficing [33], it is unclear whether the previous findings were a consequence of excessive cognitive demands, while another presentation format might have led participants to engage in a thorough comparison of the solutions. This was investigated in the present study.

2.3. Present Study

The present study compared three formats for presenting the costs of Adapt and Exchange, operationalised as the process intervention that was needed to achieve production goals. The first presentation format used the *graphs* from a previous study [10]: curves representing the thresholds for two production goals and the distance in parameter space that needed to be covered to achieve those goals. These graphs provided information in a spatial format and required considerable effort in information search and integration to compare the costs between the two solutions. In previous work, similar requirements impaired information integration [32]. Second, *separate numbers* presented the costs of Adapt and Exchange in a numerical format, and separately for each process parameter. Accordingly, comparing the solutions made it necessary to calculate the total cost for each solution by adding up the component costs. A third presentation format, *integrated numbers*, presented the overall cost of each solution as a single number and thus only required a comparison of two numbers. The aim of the present study was to investigate how these three presentation formats affect participants' decisions, leading them to either satisfice or to compare the Adapt and Exchange solutions by computing their cost ratio. Alternatively, if a satisficing strategy is generally adopted when making Adapt/Exchange decisions simply because it makes sense in this context, presentation format should have no effect. To investigate how the influence of presentation format as a surface feature depends on structural task features, two such features were varied: the absolute costs of Adapt and the cost ratio of Adapt and Exchange. If participants satisfice, only the absolute costs of Adapt should matter but not the Adapt/Exchange ratio. This was investigated in two experiments using different operationalisations of the process intervention costs. Our

stimuli, data and additional materials are made available via the Open Science Framework (<https://osf.io/8c5mz/>).

3. Experiment 1

3.1. Introduction

3.1.1. Experimental Setting

In a computer-based experiment, participants were responsible for enhancing product quality in a chemical process. Product quality depended on two factors: conversion and foam (see Figure 1a). While conversion denotes how much of the chemical has reacted and thus high conversion is an outcome to strive for, foam can occur as a side effect of chemical reactions and can destroy the product. Therefore, enhancing product quality made it necessary for participants to increase conversion, while avoiding foam. Moreover, they had to intervene with the process as little as possible, as any process intervention is risky. To reach the production goals, participants could adjust three process parameters: temperature, mixing speed, and volume. Volume and temperature could be used to increase conversion. While volume had no negative side effects, temperature also increased foaming. Therefore, temperature increases usually had to be compensated by reductions of mixing speed to avoid foaming. Goal conflicts arose from the fact that the required conversion could only be achieved by increasing volume and/or temperature, while temperature also increased foaming and thus was a non-desirable process intervention. While foam could be avoided via mixing speed, this compensation additionally increased the non-desirable process intervention (see Figure 1b). These causal relations were explained to participants in depth in a pre-experimental instruction video.

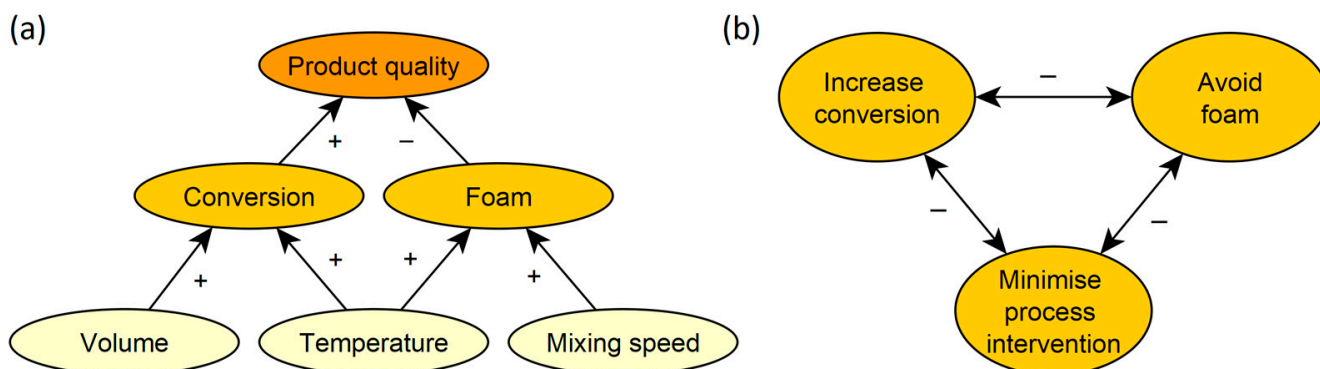


Figure 1. Causal diagrams representing the constraints in the modular plant scenario. (a) Relations between process parameters and outcomes. (b) Goal conflicts in the selection of parameter settings.

During the experiment, participants could choose between two solutions: adapting parameters in the currently used, small module or exchanging this module for a new one with a bigger reactor. This choice determined how the process parameters could be set, because the two modules had different but overlapping operating ranges. These ranges were much narrower in the current module and this determined how the production goals could be achieved by mere parameter adaptations: the required conversion could not be reached by increasing volume, because the small reactor did not allow for this. Therefore, when choosing Adapt, participants had to use temperature and compensate for its negative effects via mixing speed, which required a large process intervention. Conversely, when choosing Exchange, participants could increase volume to reach the required conversion, thus greatly reducing the changes in other parameters. However, Exchange came with an additional, non-explicit cost: the physical effort required to manually exchange the module. This cost was not included in the presentation made available to participants. Still, it was anticipated to shift participants' preferences towards choosing Adapt, although Adapt was inferior to Exchange in the explicit costs throughout the experiment. Thus, participants were confronted with a goal conflict. On the one hand, they had to minimise

the explicit costs (i.e., process intervention), but on the other hand, they also had to keep the non-explicit costs (i.e., physical effort) at an acceptable level. There was no normatively correct solution, as the solution quality depended on how participants weighted the explicit and non-explicit costs.

In the present study, and in contrast to [10], participants did not have to generate the parameter settings themselves, as each trial provided one Adapt and one Exchange solution, which participants could choose from. Both solutions led to a successful outcome, but they differed in the costs of achieving those outcomes (i.e., larger process intervention for Adapt, smaller process intervention plus physical effort for Exchange). Moreover, if participants chose Exchange, they had to perform a physical procedure that simulated the module reconfiguration.

3.1.2. Presentation Formats

Three formats for presenting the solutions were compared: graphs, separate numbers, and integrated numbers. Each provided information about the explicit costs of changing process parameters but no information about the non-explicit costs of physically exchanging the module or the associated risks.

Graphs represented the relevant relations in the chemical process (see Figure 2a). The left curve shows how the current conversion threshold depends on temperature and volume. The right curve shows how the threshold for the foam risk depends on temperature and mixing speed. All values above the left curve and below the right curve are acceptable. The graph visualisations also presented the position of the current parameter settings (visualised as a black x in Figure 2a) and their new positions, given that Adapt or Exchange was chosen (visualised as green and purple dots, respectively). In this way, participants could see how much process intervention they would need for each solution (i.e., to move from the current position to the new one). In the present study, all presented graphs provided valid solutions (i.e., all Adapt and Exchange solutions were located above the conversion curve and below the foam curve, respectively). Thus, the graphs provided information about process intervention costs in spatial form. In that sense, they were similar to the complex map format used by Söllner et al. [32]: several information elements were spatially distributed and participants had to search and integrate them in order to compare the solutions.

The second presentation format provided *separate numbers*: numeric values representing the costs of Adapt and Exchange, split up according to the parameters that had to be changed (see Figure 2c). Thus, for each solution a value was provided for temperature, one for mixing speed, and one for volume. Separate numbers corresponded to the graph visualisations in that they indicated the grid steps required for each parameter to move from the current position to the new one (see arrows in Figure 2a). Accordingly, comparing the costs of Adapt and Exchange required participants to calculate the sum of parameter changes for each solution.

The third presentation format provided *integrated numbers*: the total costs of each solution (i.e., number of required parameter steps), summed over the two relevant parameters of temperature and mixing speed (see Figure 2d). This presentation format made it easiest to compare Adapt and Exchange, as participants only had to compute the ratio of two numbers. In that sense, it was comparable to previous presentation formats that supported option evaluation, for instance, by presenting delays as days instead of dates [18–20] or presenting rewards in clear instead of fuzzy units [21].

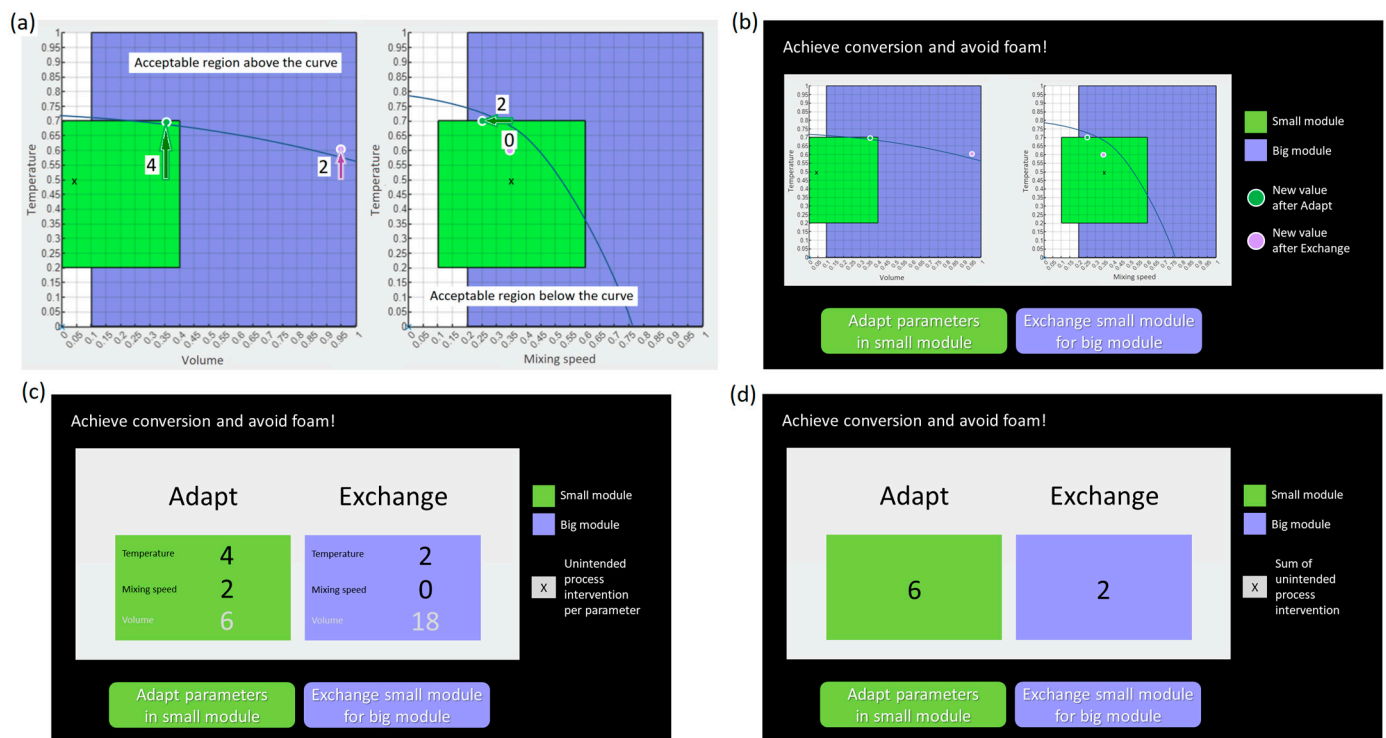


Figure 2. Stimulus material. (a) Relations between process parameters and outcomes for one trial. Green and purple background areas represent the parameter ranges of the small and big modules, curves represent the thresholds for achieving conversion (left picture) and avoiding foam (right picture). An x marks the current parameter values and the green and purple dots preview the new values for Adapt and Exchange, respectively. The Adapt/Exchange ratio is 6:2, which is generated as follows. For Adapt, six steps in the grid are needed to reach the green dot (see green arrows): four for temperature and two for mixing speed. For Exchange, two steps are needed to reach the purple dot (see purple arrows): two for temperature and zero for mixing speed. The final three parts of the figure show example screens for each presentation format: (b) graphs, (c) separate numbers, and (d) integrated numbers.

3.1.3. Adapt Costs and Adapt/Exchange Ratio

The experimental trials differed with regard to the required Adapt costs (i.e., low, medium, high). At each level of Adapt costs, the respective Exchange costs were set to produce three Adapt/Exchange ratios (i.e., 6:1, 6:2, 6:3). The presumed consequences of different decision strategies are depicted in Figure 3. If participants satisfice, their percentage of Exchange choices should only depend on the Adapt costs but not on the Adapt/Exchange ratio (see Figure 3a): they should choose Adapt as long as it is good enough, regardless of how much better Exchange might be. Conversely, if they compare the two solutions, their choices should also depend on the Adapt/Exchange ratio (see Figure 3b), with more Exchange choices at higher Adapt/Exchange ratios (i.e., more for 6:1 than 6:3). Finally, participants' strategies of satisficing versus comparing solutions might depend on the costs of Adapt. In this case, their choices should be independent of the Adapt/Exchange ratio when the Adapt costs are low but become more dependent on the Adapt/Exchange ratio as the Adapt costs increase (see Figure 3c).

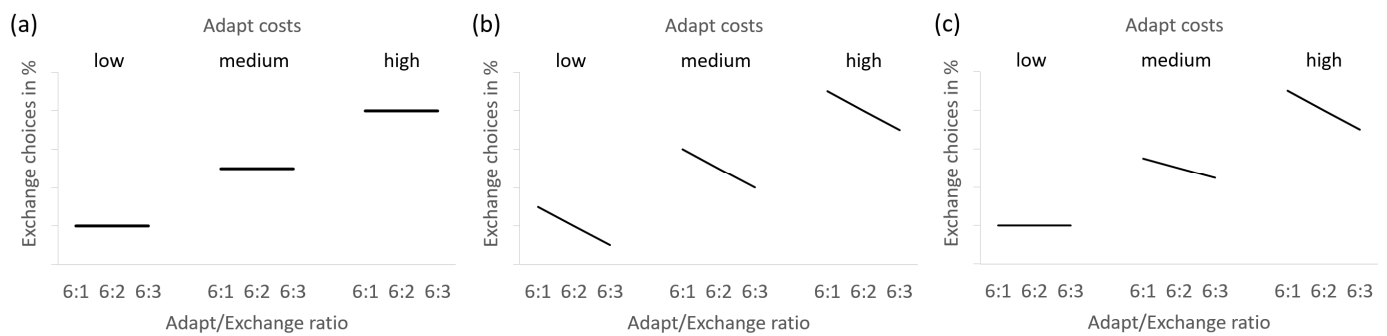


Figure 3. Presumed effects of satisficing versus comparing solutions on the percentage of Exchange choices, depending on the Adapt costs and Adapt/Exchange ratio. (a) Satisficing while completely ignoring the Adapt/Exchange ratio. (b) Always considering the Adapt/Exchange ratio. (c) Increasingly considering the Adapt/Exchange ratio as the Adapt costs increase.

3.1.4. Hypotheses

With graphs, we expected participants to satisfice (i.e., choose Adapt when it is good enough, regardless of the quality of Exchange). Conversely, with the numeric presentation formats, we expected them to compare the two solutions and thus also take the Adapt/Exchange ratio into account. Accordingly, the critical comparison was whether the percentage of Exchange choices would differ between the highest and lowest Adapt/Exchange ratio. Such effects of the Adapt/Exchange ratio were expected to be weak or absent with graphs but strong with numbers.

We also hypothesised that participants would choose Exchange more often when the Adapt costs increase. More important than this main effect, we expected a triple interaction between presentation format, Adapt/Exchange ratio, and Adapt costs: whether presentation formats are differentially sensitive to the Adapt/Exchange ratio (as an indicator of solution comparison) might depend on the costs of Adapt. With graphs, we expected participants not to compare solutions when Adapt is good enough but to compare solutions when Adapt is problematic. Thus, Adapt/Exchange ratio effects should be absent at low and medium Adapt costs but present at high Adapt costs. With the numeric presentation formats, we expected participants to generally compare solutions as a default strategy. Thus, Adapt/Exchange ratio effects should be present at all levels of Adapt costs. This also means that we only expected presentation format to affect strategy choice when the Adapt costs are sufficiently small. That is, numbers but not graphs should show effects of Adapt/Exchange ratio at low and medium Adapt costs.

We had no specific hypotheses for the differences between the two numeric formats. Both separate and integrated numbers were expected to increase solution comparison (and thus Adapt/Exchange ratio effects) compared to graphs. However, we were not sure whether the higher integration difficulty of separate numbers would impair solution comparison relative to integrated numbers. If so, this should result in lower Adapt/Exchange ratio effects for separate numbers than integrated numbers.

3.2. Methods

3.2.1. Participants

Twenty-six members of the TUD Dresden University of Technology participant pool ORSEE, ref. [34], took part in the study in exchange for course credit or EUR 7 per hour. One participant was excluded from the data analysis as she did not pass the knowledge test administered after the instruction video (see below). Thus, the final sample consisted of 25 participants (15 female, 10 male) with an age range of 19 to 68 years ($M = 28.8$, $SD = 10.6$). Participants provided written informed consent and all procedures followed the principles of the Declaration of Helsinki.

3.2.2. Apparatus and Stimuli

Instruction. Before starting the experiment, participants received an instruction that consisted of two parts: an instruction video explaining the overall scenario and four instruction screens providing specific information about the task. Both are made available via the Open Science Framework (including English transcripts).

First, participants watched an instruction video that was taken from a previous study [10]. The video was based on a Microsoft PowerPoint presentation, lasted 17 min, and used several instructional techniques to facilitate learning (e.g., advance organisers, animations, summary slides, and test questions). It consisted of three parts:

- Explanation of the chemical process with a focus on the causal relations between process parameters (i.e., volume, temperature, mixing speed) and outcomes (i.e., conversion, foam);
- Introduction to modular plants, characteristics of the small and big module with regard to the process parameters, and positive/negative effects of Adapt and Exchange;
- Instruction concerning the materials and decisions in the experiment, as well as the following rules of thumb: (1) parameter changes are risky for the product and thus you should change as few parameters as possible, and change each parameter as little as possible; (2) volume does not harm the process; (3) temperature is the parameter with the strongest positive and negative effects; and (4) usually, there is more than one correct solution.

The last part of the video provided an instruction for the experiment. It explained the stimuli in detail and used an animated example as a step-by-step demonstration of how the new parameter values in graphs were determined. Specifically, participants were told that conversion was reached when the position of the x was above the left curve, which meant that the temperature had to be increased from value T_1 to value T_2 . It was also stated that as a consequence of this increase, the x in the right picture moved to T_2 as well and therefore its new position was above the foam curve. Therefore, it was necessary to reduce the mixing speed from value S_1 to S_2 . The instruction did not refer to steps of process intervention but only indicated the initial and final parameter values. It also did not suggest any strategies for choosing between Adapt or Exchange. Instead, it used the same stimulus to first demonstrate the procedure given that Adapt was chosen and then a second time given that Exchange was chosen.

The instructions for the specific task in the current experiment were provided within the experiment programme on four consecutive screens. The first screen informed participants that they would have to choose between Adapt and Exchange, that they should choose the solution that seems best to them, and that in order to make their decision, they would either see pictures or numbers in different trials. The next three screens provided instructions for each presentation format by showing a stimulus example and explaining its content. For graphs, the explanation of the stimulus only focused on the green and purple dots (representing the post-adjustment parameter values), as all the other content had already been covered in the video. For separate numbers, participants read that the numbers indicated how much process intervention was needed for Adapt and Exchange, respectively. For integrated numbers, they read that the numbers show the sum of temperature and mixing speed interventions and that volume was not included in the calculation. Moreover, the three instruction screens reminded participants that interventions should be kept to a minimum and informed them that they would not have to set the parameters themselves but merely choose the solution that seems best to them.

Experiment. The experiment took place in a quiet lab room, where up to three participants worked in parallel during each session, using one of three laptops (13, 14 and 15.6", respectively) and a standard computer mouse as an input device. The experiment was programmed with the Experiment Builder (SR Research, Ontario, Canada). Example stimuli are presented in Figure 2. All the stimuli were displayed at a resolution of 1920×1080 pixels. They presented pictures, interaction elements, and text in white font on a black background. Consistent colour coding was used for Adapt/small module (i.e.,

green) and Exchange/big module (i.e., purple). All text was presented in German. Each stimulus included the following elements: (1) a textual request to achieve conversion and avoid foam, (2) the actual graph or number stimulus, (3) a legend explaining the content of the graph or number stimulus, as well as (4) a green button to choose Adapt and a purple button to choose Exchange.

Graphs were shown in two adjacent pictures and visualised how the costs of the two solutions resulted from the process parameter changes (see Figure 2b). Each picture reflected how one outcome depended on the interaction of two parameters: for conversion (left picture), the relation between temperature on the *y*-axis and volume on the *x*-axis reflected whether any given parameter value combination was able or unable to exceed the conversion threshold. This threshold was exceeded for all value combinations above the curve, while all value combinations below the curve were invalid as they did not achieve the required conversion. For foam (right picture), the relation between temperature on the *y*-axis and mixing speed on the *x*-axis reflected whether any given parameter value combination was able or unable to stay below the acceptable foam risk. All combinations below the curve met this foam requirement. The slopes and positions of the curves changed between trials. In all graphs, green and purple background boxes visualised the parameter ranges of the small and big module, respectively. These ranges were fixed throughout the experiment. The current parameter settings were marked by a black *x* in both pictures. Moreover, two solutions (i.e., new parameter values) were included in each graph, one for Adapt (green dot) and one for Exchange (purple dot). These dots were always positioned above the conversion curve and below the foam curve, thus reflecting valid solutions. They also reflected the minimal process intervention and thus the best possible outcome achievable with either solution. Their distance to the current parameter values (i.e., to the *x*) reflected the Adapt and Exchange costs. This distance was measured in the number of horizontal grid cells for temperature and vertical grid cells for mixing speed, which we will refer to as steps. One step corresponded to one grid cell (i.e., 0.5 units on the temperature or mixing speed scale). Volume was ignored and did not contribute to the step count, because increasing it had no cost.

Separate numbers represented the costs of Adapt and Exchange in terms of the process intervention needed for each individual parameter (see Figure 2c). Thus, these numbers also reflected the number of steps (i.e., grid cells to be travelled in the graphs). While temperature and mixing speed steps were presented in black font, volume steps were presented in grey font, as they were irrelevant and could be ignored. For the stimuli with integrated numbers (see Figure 2d), the steps required for temperature and mixing speed were added up and thus only a single number was shown for each solution. In both numeric formats, these steps or costs were represented in a green box for Adapt (left) and a purple box for Exchange (right).

Adapt always yielded higher costs than Exchange. However, the stimuli differed in their absolute magnitude of Adapt costs (i.e., 3, 6 or 18 steps) and in the Adapt/Exchange ratio (i.e., 6:1, 6:2, or 6:3). Table 1 illustrates how the Exchange costs depended on the Adapt costs and Adapt/Exchange ratio. For instance, in a trial with an Adapt cost of 18 steps and an Adapt/Exchange ratio of 6:2, Exchange required 6 steps.

Table 1. Exchange costs (steps) in Experiment 1, depending on the Adapt costs and Adapt/Exchange ratio.

		Adapt/Exchange Ratio		
		6:1	6:2	6:3
Adapt costs (steps)	3	0.5	1	1.5
	6	1	2	3
	18	3	6	9

Since each trial had its own stimulus, a total of 110 process graphs were generated for 90 relevant trials (corresponding to 10 instances of the 9 combinations in Table 1) and

20 filler trials (see below). The detailed procedure for generating the graphs is described in Appendix A. The stimuli differed in their assignment of the total costs to temperature and mixing speed steps. For instance, an integrated cost of 6 steps could result from a temperature increase of 4 and a mixing speed decrease of 2 steps, or it could result from a change of both parameters by 3 steps. The stimuli also differed in the number of required volume steps, although volume was not included in the step calculations. The exact same step numbers that were represented in graphs were also used in the numeric presentation formats.

The *physical module exchange* was simulated using five Mega Bloks® (i.e., big, coloured plastic blocks) that were placed next to participants' laptops.

3.2.3. Procedure

Instruction, practice, and knowledge test. After being welcomed and signing the consent form, participants watched the instruction video. Afterwards, they completed five practice tasks on paper, in which they were shown graphs and had to generate a solution. These graphs only contained the current parameter values but not the new, intended values. Participants had to choose a solution (Adapt or Exchange) and set the parameters (i.e., volume, temperature, and mixing speed) to their new values with a pen. In doing so, they had to make sure to move above the conversion curve and stay below the foam curve. Their solutions were subsequently checked by the experimenter. In case of errors, she provided feedback and used the erroneous examples to explain again how the parameter values had to be set. After the practice task, participants performed a written multiple-choice knowledge test to assess their understanding and memory of the instruction. While all participants were allowed to take part in the experiment, a criterion of 70% correct answers was used to decide whether the data would be analysed. Taken together, the instruction, practice, and knowledge test took about 30–45 min and the entire experiment took about 1.5 h.

Experiment. The experiment used a three-factorial within-subjects design: 3 (*presentation format: graphs, separate numbers, integrated numbers*) \times 3 (*Adapt costs: 3, 6, 18 steps*) \times 3 (*Adapt/Exchange ratio: 6:1, 6:2, 6:3*). During the experiment, participants performed 9 practice trials (3 for each presentation format) and 330 experimental trials. The latter consisted of 270 relevant trials: 10 repetitions of each combination of the 3 factors (i.e., presentation format, Adapt costs, Adapt/Exchange ratio). Additionally, they included 60 filler trials: 10 repetitions per presentation format of 2 irrelevant cost factor combinations (i.e., 3 Adapt steps with an Adapt/Exchange ratio of 6:6, and 18 Adapt steps with an Adapt/Exchange ratio of 6:0.33). These filler trials had been added to make the step distributions appear balanced to participants (by including 3 and 1 absolute Exchange steps in each Adapt cost condition). However, they were not included in the data analysis. The trial order was randomised across the experiment, individually for each participant. The experiment was split into 6 blocks, allowing participants to take breaks after each 55 trials.

Each trial started with a choice screen that presented the graphs or numbers (see Figure 2b–d). Participants had to choose between Adapt and Exchange by clicking one of the two buttons. Clicking the “Adapt” button led them to a neutral screen with only the background objects (i.e., grey field, buttons, and legend) but no graphs or numbers. After 300 ms, the next trial started. Clicking the “Exchange” button transferred participants to an exchange screen that prompted them to perform the physical module exchange. To simulate this procedure, they had to re-stack a pile of five Mega Bloks® upside down. The minimum time for the module exchange task was set to five seconds and only after this interval the “Finish” button became active. On average, it took participants 7.2 s to complete the block stacking task. After clicking the “Finish” button, the neutral screen was presented for 300 ms and then the next trial started. No deadline or time constraint was placed on participants' responses.

Moreover, participants did not receive feedback about their choices. This is because all the solutions presented in this study were valid, in the sense that they achieved the

binary conversion and foam goals (i.e., not exceeding the thresholds). We decided to keep goal achievement in this binary format instead of quantifying it, for instance, by varying the amount of conversion that could be achieved. This simplification was chosen for two reasons. First, we wanted to keep task complexity at a manageable level. More importantly, we wanted to investigate the effects of varying the Adapt and Exchange costs as well as their ratio. This would have been much more complicated if participants had additionally needed to integrate information about these costs with information about goal achievement. One might argue that we could still have provided feedback about the quality of choices based on the costs alone (e.g., negative feedback if a participant chose Adapt when the Adapt/Exchange cost ratio was 18:3). However, we decided not to do this, because the evaluation of solution quality depends on how participants set their subjective criteria. For instance, whether it is good or bad to choose Adapt with a ratio of 18:3 depends on how you trade off the higher process intervention costs of Adapt and the physical effort of Exchange. We will return to this issue in the General Discussion.

3.2.4. Data Analysis

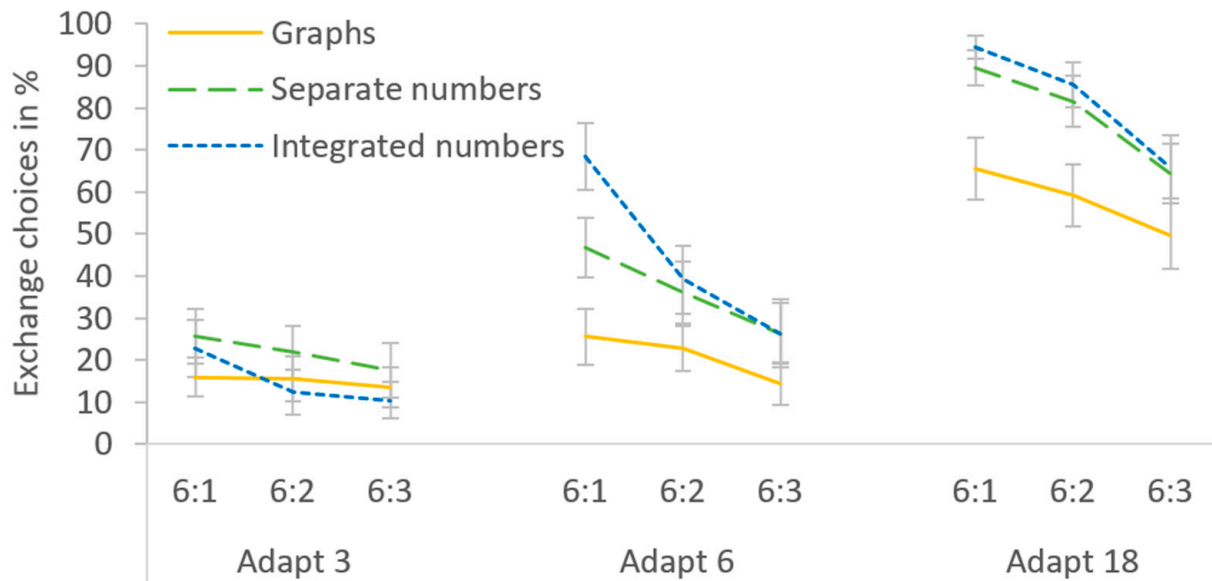
To test whether participants satisficed or compared solutions when using the three presentation formats, the mean percentage of Exchange choices was analysed using a 3 (presentation format: graphs, separate numbers, integrated numbers) $\times 3$ (Adapt costs: 3, 6, 18 steps) $\times 3$ (Adapt/Exchange ratio: 6:1, 6:2, 6:3) repeated measures ANOVA. Only effects including the factor presentation format are reported, as only these effects are relevant regarding the purpose of the study. An alpha value of $p = 0.05$ was used to determine statistical significance, and all pairwise comparisons were performed with Bonferroni correction. No participants or trials were excluded from the analyses as outliers based on their solution times or decision outcomes, because we saw no theoretical justification to do so. Particularly, long solution times might reflect a very thorough analysis of the available information. Similarly, a high preference for a particular solution might reflect an intentional, strategic choice. That is, some participants might simply consider the higher process intervention costs of Adapt to be much more important than the physical effort of Exchange, or vice versa, leading them to believe that the respective other option should be avoided in general. To still give readers the chance to estimate the effects of outliers on our results, we present the choices of individual participants graphically. All data are available in our repository at the Open Science Framework: <https://osf.io/8c5mz/>. In this repository, we also provide additional analyses of solution times, which were omitted from the main article to keep it focused on our main questions.

3.3. Results

Overall, Exchange was chosen in 41.4% of the trials, and Table 2 provides an overview of the means for each cell. When comparing the mean percentage of Exchange choices between the experimental conditions, all main effects and interactions were significant (see Figure 4). First, a main effect of presentation format, $F(2,48) = 7.375$, $p = 0.002$, $\eta_p^2 = 0.235$, indicated that the rate of Exchange choices differed between the presentation formats. Pairwise comparisons revealed that Exchange was chosen less often with graphs than with separate and integrated numbers (31.4 vs. 45.6 and 47.3%), both $ps < 0.03$, while the two numeric formats did not differ, $p > 0.9$. Second, a main effect of Adapt costs, $F(2,48) = 72.151$, $p < 0.001$, $\eta_p^2 = 0.750$, indicated that Exchange choices depended on Adapt costs. Specifically, Exchange was chosen more frequently with increasing Adapt costs (17.3, 34.0 and 72.9% for 3, 6 and 18 Adapt steps, respectively), all $ps < 0.002$. Third, a main effect of Adapt/Exchange ratio, $F(2,48) = 33.206$, $p < 0.001$, $\eta_p^2 = 0.585$, indicated that Exchange choices also depended on the Adapt/Exchange ratio. In particular, Exchange was chosen most often with an Adapt/Exchange ratio of 6:1, followed by 6:2 and 6:3 (50.5, 41.6 and 32.1%), all $ps < 0.002$.

Table 2. Means and standard deviations (in parentheses) for the percentage of Exchange choices in Experiment 1, depending on presentation format, Adapt costs, and Adapt/Exchange ratio.

Adapt Costs		Adapt 3			Adapt 6			Adapt 18		
Adapt/Exchange Ratio	6:1	6:2	6:3	6:1	6:2	6:3	6:1	6:2	6:3	
Graphs	16.0	15.6	13.6	25.6	22.8	14.4	65.6	59.2	49.6	
	(23.3)	(26.3)	(24.1)	(32.8)	(26.9)	(25.8)	(37.3)	(36.7)	(39.0)	
Separate numbers	25.6	22.0	17.6	46.8	36.0	26.4	89.6	81.6	64.4	
	(32.7)	(30.7)	(32.3)	(35.3)	(37.1)	(35.6)	(21.1)	(30.4)	(35.8)	
Integrated numbers	22.8	12.4	10.4	68.4	39.2	26.4	94.4	85.6	66.0	
	(34.6)	(27.0)	(21.7)	(39.3)	(40.2)	(40.5)	(13.9)	(26.6)	(37.5)	

**Figure 4.** Percentage of Exchange choices in Experiment 1, depending on presentation format, Adapt costs, and Adapt/Exchange ratio. Error bars represent standard errors of the mean.

There also was an interaction of presentation format and Adapt costs, $F(4,96) = 4.701$, $p = 0.002$, $\eta_p^2 = 0.164$. The reduced Exchange rate with graphs was restricted to medium and high Adapt costs. With only 3 Adapt steps, the presentation formats did not differ, all $ps > 0.4$. With 6 steps, graphs led to fewer Exchange choices than integrated numbers, $p = 0.007$, but the difference to separate numbers missed the significance level, $p = 0.057$. With 18 steps, graphs led to fewer Exchange choices than both numeric formats, both $ps < 0.02$. Thus, when the process intervention required for Adapt was low, presentation format did not affect choice, but as the Adapt costs increased, graphs seemed to discourage Exchange. No difference between the numeric formats was detected at any level of Adapt costs, all $ps > 0.4$.

Moreover, there was an interaction of presentation format and Adapt/Exchange ratio, $F(4,96) = 8.158$, $p < 0.001$, $\eta_p^2 = 0.257$. Exchange was chosen more often with the highest Adapt/Exchange ratio of 6:1 than with the lowest ratio of 6:3 for all presentation formats, all $ps < 0.003$. This ratio dependence was smaller with graphs than with separate numbers and integrated numbers (with differences of 9.9 vs. 17.9 and 27.6%, respectively). Still, we found significant Adapt/Exchange ratio effects for graphs. This disconfirms the hypothesis that graphs generally induce satisficing, which should have rendered the Adapt/Exchange ratio irrelevant.

The triple interaction of presentation format, Adapt costs, and Adapt/Exchange ratio just reached significance, $F(8,192) = 1.997$, $p = 0.049$, $\eta_p^2 = 0.077$, reflecting that Adapt costs were critical in determining whether the presentation formats differed in their sensitivity to the Adapt/Exchange ratio. With low Adapt costs of 3 steps, no presentation format led to differences between the Adapt/Exchange ratios, all $ps > 0.1$. For all presentation formats, Adapt was chosen most of the time, regardless of how much better Exchange

might be (which suggests that participants satisfied). Conversely, with high Adapt costs of 18 steps, the Adapt/Exchange ratio influenced choices, regardless of presentation format. Exchange was always chosen more often at the highest than the lowest Adapt/Exchange ratio, all $ps < 0.03$ (which suggests that participants compared the solutions). Differences between the presentation formats in their sensitivity to the Adapt/Exchange ratio were only observed with medium Adapt costs of 6 steps. Here, the difference between the highest and lowest Adapt/Exchange ratio was present for both numeric formats, both $ps < 0.003$, but absent for graphs, $p = 0.198$. Any trend for Adapt/Exchange ratio effects with graphs at 6 Adapt steps that might seem apparent in Figure 4 was exclusively due to two participants with extreme values (see Figure 5a).

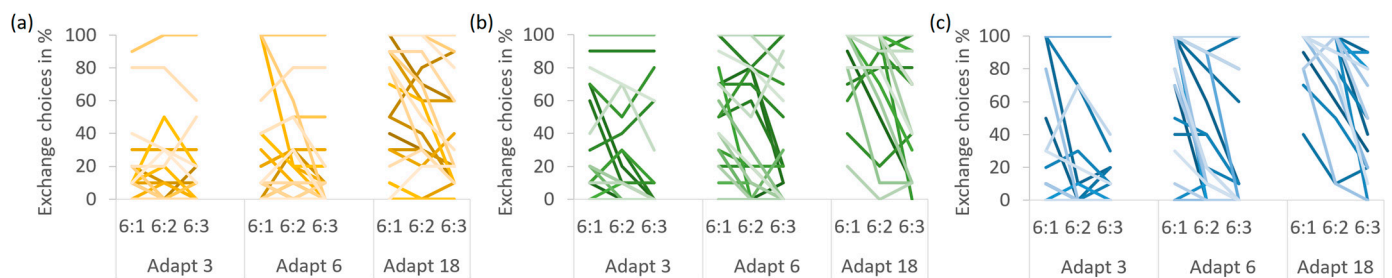


Figure 5. Individual percentages of Exchange choices in Experiment 1 for each presentation format, depending on the Adapt costs and Adapt/Exchange ratio. (a) Graphs, (b) separate numbers, and (c) integrated numbers. Each line represents the data of one participant.

Despite these general effects, there was a high interindividual variation in participants' choices (see Figure 5). For instance, some participants switched between never choosing Exchange at 3 and 6 Adapt steps to always choosing it at 18 Adapt steps, especially with integrated numbers. In fact, several participants displayed ceiling effects at 18 Adapt steps, choosing Exchange in 100% of the trials, regardless of the Adapt/Exchange ratio. One participant even chose Exchange in all but one trial across the entire experiment, while others rarely chose it at all.

3.4. Discussion

Experiment 1 examined how strategies for making Adapt/Exchange decisions depend on the format in which the costs of both solutions are presented. It was hypothesised that graphs induce satisficing, because they pose higher demands on information search and integration, thereby making it harder to compare the solutions. Therefore, Exchange choices should be independent of the Adapt/Exchange ratio, which indicates satisficing. Conversely, a presentation of costs as numbers was hypothesised to facilitate solution comparison, leading to more Exchange choices with higher Adapt/Exchange ratios.

The picture that emerged from the results is more complex. The presentation formats indeed showed differential sensitivity to the Adapt/Exchange ratio, but only with medium Adapt costs. In this case, the effects supported our hypotheses. That is, with graphs, participants seemed to satisfice instead of comparing solutions: the frequency of Exchange choices did not depend on the Adapt/Exchange ratio. With both numeric formats, participants did compare the solutions: they chose Exchange more often when the Adapt/Exchange ratio was high. Thus, when the situation was ambiguous regarding the quality of the status quo (i.e., medium Adapt costs), presentation format mattered. A different picture emerged when the Adapt costs became more extreme in either direction. With low Adapt costs, participants satisficed irrespective of presentation format: no presentation format revealed Adapt/Exchange ratio effects but participants simply chose Adapt, regardless of whether Exchange led to better outcomes. With high Adapt costs, participants compared the solutions irrespective of presentation format: all presentation formats revealed Adapt/Exchange ratio effects. This is interesting, as it shows that participants were clearly

capable of comparing the solutions with graphs. Thus, graphs did not make solution comparison impossible but merely discouraged it when it was not necessary.

An unexpected finding was the main effect of presentation format: participants chose Exchange less often with graphs than with both numeric formats. On the one hand, this might be a genuine consequence of the different presentation formats. On the other hand, it might have resulted from how the numbers were generated. They represented the steps needed to move above the conversion curve and below the foam curve in the process graphs, ranging from 0.5 to 18. However, the axes of the graphs did not represent steps but standardised process units, ranging from 0 to 1. Accordingly, the numbers shown to participants were larger in the numeric formats.

The presentation formats were not necessarily inconsistent, because in fact, we do not know how participants represented the process intervention costs with graphs. Given the salient grid markings, it is likely that they thought of them as steps (i.e., in the same unit as the numeric formats). However, it is also possible that participants were aware of the difference in scale and thus adjusted their behaviour accordingly. Previous research suggests that this might be consequential. First, higher reward magnitudes in intertemporal choice make people more inclined to choose the larger/later reward [35]. Similarly, the higher absolute costs in the numeric formats might have discouraged participants from choosing the costly Adapt solution. Second, in multi-attribute decision-making, expanded numeric scales (e.g., costs per year instead of per month) make people more inclined to choose the solution that performs better on the expanded attribute [30]. Similarly, the disadvantage of Adapt might have seemed larger for the numeric formats. To control for such effects of inconsistent scales, in Experiment 2 the numbers were changed from steps to process units, so that the process intervention cost was measured on the same scale for all three presentation formats.

4. Experiment 2

4.1. Introduction

The aim of Experiment 2 was twofold. First, we intended to replicate the independence of choices from the Adapt/Exchange ratio with graphs at medium Adapt costs. Second, we eliminated a confound of Experiment 1, where presentation formats had differed in the numeric scaling of costs. In Experiment 2, all presentation formats used the same scale to represent process interventions (i.e., 0–1). If the effects of presentation format in Experiment 1 had resulted from different scales, they should disappear. If they had actually resulted from graphs hampering the comparison of Adapt and Exchange, they should remain intact.

However, changing the scale of costs had another consequence: The numeric formats now had to use a varying number of decimal places. Accordingly, neither the magnitude of the single digits nor the length of the string could be used by participants to evaluate the required process intervention (e.g., 0.1 is larger than 0.075 but the latter has higher digit values and is longer). Decimals are not processed automatically, and string length strongly influences their processing [36]. The use of decimals can also affect decision making and lead to less discounting in intertemporal choice [37]. A higher difficulty in comparing the costs of the two solutions might decrease the dependence of choices on the Adapt/Exchange ratio. In Experiment 1, stronger Adapt/Exchange ratio effects were observed with numbers than graphs. If this was because the numbers facilitated comparison, the difference between presentation formats should be reduced or absent in Experiment 2. Particularly, the Adapt/Exchange ratio effects for separate numbers should become more similar to graphs because participants had to compare and additionally add decimal numbers.

Taken together, changing the numeric scale has two consequences: it lowers the cost magnitudes and increases the difficulty of comparing decimals. Both should reduce the differences between presentation formats. Particularly, the main effect of presentation format and the interaction of presentation format and Adapt/Exchange ratio should disappear, if

they had only been a consequence of low-level factors in the scaling of numbers. Instead, if they reflected a genuine effect of presentation format, they should remain intact.

4.2. Methods

4.2.1. Participants

Twenty-eight members of the TUD Dresden University of Technology participant pool ORSEE [34] took part in the study in exchange for course credit or EUR 7 per hour. Three participants were excluded from the data analysis: one because she displayed a severe lack of understanding and could not even solve the practice task, and two because they did not pass the knowledge test. Thus, the final sample consisted of 25 participants (15 female, 10 male) with an age range of 19 to 47 years ($M = 27.3$, $SD = 7.2$). Participants provided written informed consent and all procedures followed the principles of the Declaration of Helsinki.

4.2.2. Apparatus and Stimuli

The stimulus material was identical to that in Experiment 1, with the following exception: the numeric formats now represented units of process intervention instead of steps and thus matched the scale of the graph axes, ranging from 0 to 1. To this end, all the numbers from Experiment 1 were divided by 20. Note that this resulted in decimal numbers with varying string lengths (see Table 3).

Table 3. Exchange costs (units) in Experiment 2, depending on the Adapt costs and Adapt/Exchange ratio.

		Adapt/Exchange Ratio		
		6:1	6:2	6:3
Adapt costs (units)	0.15	0.025	0.05	0.075
	0.3	0.05	0.1	0.15
	0.9	0.15	0.3	0.45

4.2.3. Procedure

The procedure was identical to that in Experiment 1.

4.2.4. Data Analysis

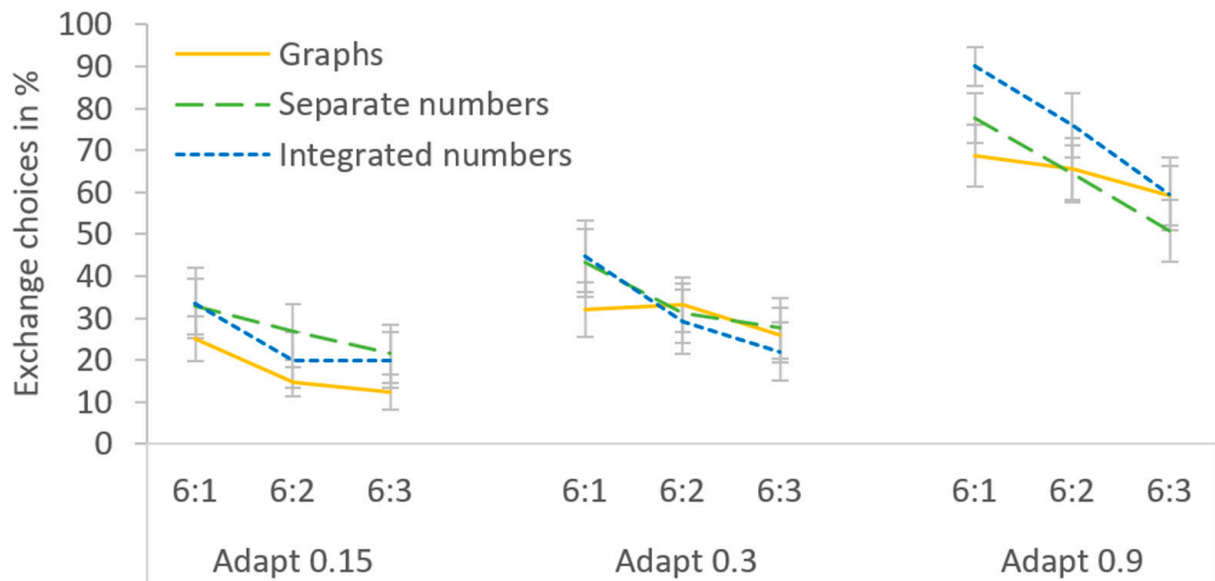
The methods of analysing the data were identical to Experiment 1 and only the levels of the Adapt cost factor in the repeated measures ANOVA were different: 3 (*presentation format: graphs, separate numbers, integrated numbers*) \times 3 (*Adapt costs: 0.15, 0.3, 0.9 units*) \times 3 (*Adapt/Exchange ratio: 6:1, 6:2, 6:3*). All data are made available via the Open Science Framework: <https://osf.io/8c5mz/>.

4.3. Results

Overall, Exchange was chosen in 41.1% of the trials, and Table 4 provides an overview of the means for each cell. When comparing Exchange choices between the experimental conditions (see Figure 6), a first striking result was that the main effect of presentation format was completely absent, $F < 1$. Exchange choices did not differ between graphs, separate numbers, and integrated numbers (37.5 vs. 41.8 and 43.9%), all $ps > 0.9$. Second, there was a main effect of Adapt costs, $F(2,48) = 60.541$, $p < 0.001$, $\eta_p^2 = 0.716$. Pairwise comparisons indicated that Exchange was chosen more often when Adapt was more costly (23.0, 32.1 and 68.0% for 0.15, 0.3 and 0.9 Adapt units, respectively), all $ps < 0.001$. Third, a main effect of Adapt/Exchange ratio, $F(2,48) = 16.362$, $p < 0.001$, $\eta_p^2 = 0.716$, revealed a dependence of choices on this ratio. Exchange was chosen most often with an Adapt/Exchange ratio of 6:1, followed by 6:2 and 6:3 (50.0, 40.1 and 33.2%), all $ps < 0.007$.

Table 4. Means and standard deviations (in parentheses) for the percentage of Exchange choices in Experiment 2, depending on presentation format, Adapt costs, and Adapt/Exchange ratio.

Adapt Costs	Adapt 0.15			Adapt 0.3			Adapt 0.9		
Adapt/Exchange Ratio	6:1	6:2	6:3	6:1	6:2	6:3	6:1	6:2	6:3
Graphs	25.2 (26.8)	14.8 (17.6)	12.4 (20.3)	32.0 (32.9)	33.2 (32.2)	26.0 (31.9)	68.8 (37.2)	65.6 (37.1)	59.2 (35.6)
Separate numbers	32.8 (33.5)	26.8 (33.4)	21.6 (34.7)	43.2 (41.0)	31.2 (34.9)	27.6 (35.7)	77.6 (29.5)	64.4 (33.9)	50.8 (36.4)
Integrated numbers	33.6 (41.7)	20.0 (33.4)	20.0 (33.5)	44.8 (42.8)	29.2 (38.3)	22.0 (34.4)	90.0 (23.5)	76.0 (38.0)	59.6 (43.5)

**Figure 6.** Percentage of Exchange choices in Experiment 2, depending on presentation format, Adapt costs, and Adapt/Exchange ratio. Error bars represent standard errors of the mean.

The interaction of presentation format and Adapt costs was not significant, $F(4,96) = 1.628$, $p = 0.173$, $\eta_p^2 = 0.064$, indicating that presentation formats did not differ for any level of Adapt costs, all $ps > 0.3$. However, there was a significant interaction of presentation format and Adapt/Exchange ratio, $F(4,96) = 3.023$, $p = 0.021$, $\eta_p^2 = 0.112$. Although Exchange was chosen more often with an Adapt/Exchange ratio of 6:1 than with 6:3 for all presentation formats, all $ps < 0.02$, this difference between the highest and lowest Adapt/Exchange ratio was smaller with graphs than with separate numbers or integrated numbers (9.5 vs. 17.9 and 22.3%). However, again, these data do not support the hypothesis that the Adapt/Exchange ratio is generally irrelevant with graphs.

The triple interaction of presentation format, Adapt costs and Adapt/Exchange ratio did not reach significance, $F(8,192) = 1.722$, $p = 0.096$, $\eta_p^2 = 0.067$. However, pairwise comparisons indicated that the Adapt costs determined whether the presentation formats differed in their sensitivity to the Adapt/Exchange ratio. With low Adapt costs, the difference between the highest and lowest Adapt/Exchange ratio was significant for graphs and separate numbers, both $ps < 0.05$, but not for integrated numbers, $p = 0.089$. With medium Adapt costs, this Adapt/Exchange ratio effect was absent for graphs, $p = 0.787$, but present for both numeric formats, both $ps < 0.02$. With the highest Adapt costs, the Adapt/Exchange ratio effect missed the significance level for graphs, $p = 0.068$, but was highly significant for both numeric formats, both $ps < 0.005$. Thus, similar to Experiment 1, the most pronounced influence of presentation format on whether participants compared the solutions was observed with medium Adapt costs: when using graphs, it did not matter whether Exchange was much better than Adapt, while when using the numeric formats, it did. Just like in Experiment 1, there were considerable interindividual differences in the percentage of Exchange choices (see Figure 7).

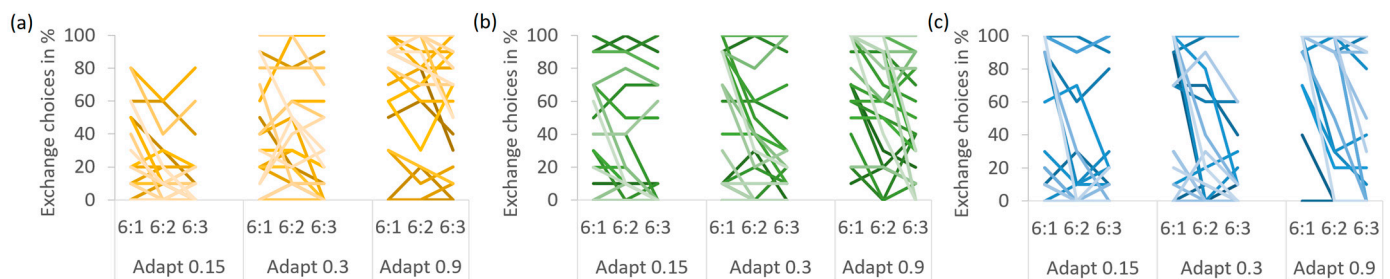


Figure 7. Individual percentages of Exchange choices in Experiment 2 for each presentation format, depending on the Adapt costs and Adapt/Exchange ratio. (a) Graphs, (b) separate numbers, and (c) integrated numbers. Each line represents the data of one participant.

4.4. Discussion

Experiment 2 aimed to replicate the main findings of Experiment 1 while eliminating a potential confound in the scaling of the numbers. Therefore, all numbers were presented on the same scale as the graph units. This indeed made participants choose Exchange similarly often with all presentation formats. However, this was not only due to a decrease in Exchange choices with the numeric formats but also resulted from a concurrent increase with graphs. A reason for this unexpected result might be that participants in Experiment 2 matched their Exchange choices between the presentation formats more closely, because the identical scale now made it more obvious that all formats represented the same thing.

The most important finding of Experiment 2 was that presentation format still interacted with the Adapt/Exchange ratio, suggesting that participants were less likely to compare the solutions with graphs than numbers (as indicated by weaker ratio effects for graphs). For the numeric formats, the ratio effects remained intact, despite the altered number scale (including decimal places and different string lengths), which should have made solution comparison more difficult. Similar to Experiment 1, the difference between the presentation formats was most pronounced with medium Adapt costs. In this condition, ratio effects were completely absent with graphs but substantial with the numeric formats. The finding that in ambiguous situations, participants compare solutions with numbers but not with graphs thus seems to be robust.

A curious finding from Experiment 2 was that in contrast to Experiment 1, graphs produced Adapt/Exchange ratio effects when only a small process intervention was necessary (i.e., with low Adapt costs). Currently, it is unclear how to interpret this result. However, given that for graphs, the stimulus material did not differ from Experiment 1 in any way, it might well be a chance finding and should be replicated before drawing conclusions.

5. General Discussion

In many situations, problem solvers have to choose between local and global changes. Should they merely adapt a currently used solution or exchange it for a completely new one? Previous research suggested that people do not thoroughly compare these solutions but merely check whether the status quo is good enough [9,10]. But how does this selection of decision strategies depend on the constraints of the decision context or features of the task? The present study investigated the role of structural features (i.e., solution costs) and surface features (i.e., presentation format) of Adapt/Exchange decisions. In two experiments using a modular plant scenario, participants either had to base their decisions on a graph visualisation of process relations, on numeric information about the costs for each process parameter, or on an integrated presentation of the total costs of each solution. Both experiments revealed that the presentation format does indeed affect whether people satisfice or base their choices on differences between the costs of the two solutions. However, this format dependence was most pronounced when the situation was ambiguous regarding the costs of the status quo. In contrast, people were generally less likely to perform a thorough comparison of solutions when the status quo only had minimal costs and more likely when the status quo was very costly. These findings emphasise that

decision strategies are flexible and depend on an interplay between structural and surface features of the decision context.

Before turning to a detailed discussion of these results, we first want to address a general concern about their validity. Given that all available solutions were valid and participants did not receive feedback, one might assume that they simply chose randomly or tried to avoid the physical effort of performing the physical Exchange procedure. However, such strategies do not seem likely in light of our findings. First, a general focus on effort avoidance is at odds with the overall Exchange rate being about 41% in both experiments. This means that on average, a participant performed the block stacking task 137 times. Just trying to avoid effort should have resulted in much lower Exchange rates. Second, the argument of random choice seems more consistent with the overall Exchange rate being close to 50%. However, it is unclear how random choice could have generated the complex, differentiated, and replicable pattern of results. For instance, we found the strongest evidence for solution comparison (i.e., dependence on Adapt/Exchange ratio) at high Adapt costs. These trials in particular place high cognitive demands on participants because the numbers are large and it is more difficult to count the steps in a graph. Still, exactly these trials provided evidence for non-arbitrary choices that depended on the specific cost values and their ratios. This seems inconsistent with the assumption that participants chose randomly due to their low motivation. A low motivation should have decreased participants' willingness to invest cognitive effort in difficult trials rather than increased it. In sum, participants' high Exchange rates and their differentiated patterns of results suggest that they were sufficiently motivated to engage in the task. The potential mechanisms of this engagement will be discussed in the following sections.

5.1. How Do Adapt/Exchange Decisions Depend on Presentation Format?

In the present study, decision strategies depended on the format in which the costs of two solutions were presented. These effects of presentation format were substantial, even though it was varied in random order, so that the graphs were interspersed with the numeric formats. This experimental setup puts the presentation format effects to a critical test, as it emphasises that, in fact, all three formats reflected the same choice situation. Indeed, several participants remarked during the debriefing that they had found it quite striking to observe themselves making different choices with different presentation formats, despite knowing that the situation was the same. Still, the robustness of presentation format effects does not mean that a particular presentation forced participants into using a particular strategy. With graphs, participants also compared solutions (as indicated by Adapt/Exchange ratio effects), namely when the Adapt costs were high. With the numeric formats, they also satisficed (as indicated by an absence of Adapt/Exchange ratio effects), namely when the Adapt costs were low. Thus, surface features like the presentation format only seem to encourage particular decision strategies when the circumstances are favourable. This is in line with the notion that the structure of the environment determines the selection and implementation of decision strategies [15].

It is remarkable that while graphs provided the most information, they promoted the most "quick and dirty" decision strategy (i.e., satisficing instead of comparing solutions). This is interesting because all the information provided by the numeric formats was also included in the graphs, along with ample additional information (e.g., conversion and foam thresholds, current and new parameter values, distance from the module boundaries). At least three explanations are conceivable. First, satisficing with graphs might have resulted from *information overload* [38], as the graphs might have given participants a hard time extracting the relevant information. This also is in line with the finding that the use of heuristics in multi-attribute decision-making increases with task complexity [39] and with the need to search and integrate information [31,32]. Second, satisficing might have resulted from the *specific information contents* of the graphs. For instance, they made the module boundaries visible, potentially emphasising that all the solutions could be realised within these boundaries. In principle, the instructions had also made it explicit that all

the solutions were valid. However, perhaps it became more salient with graphs. This is in line with design guidelines suggesting that clearly visible boundaries (i.e., constraints as containers) facilitate situation evaluation [40]. Third, graphs presumably increased the *saliency of the industrial domain* compared to numbers, which could represent anything in principle, cf. [27]. Thus, participants might have been reminded of the complex, non-explicit domain constraints beyond the mere Adapt/Exchange ratio. Accordingly, this ratio might no longer have been sufficient to guide their choices. Following this line of reasoning, satisficing is not a “quick and dirty” strategy after all. Instead, it is a rational adaptation that makes perfect sense once the scenario exceeds a certain degree of complexity.

All three explanations rest on the assumption that the additional information provided in the graphs drew participants’ attention away from the explicit costs. However, they make different assumptions about how the information was processed and how this induced satisficing. The first explanation assumes that the additional information exceeded participants’ cognitive limitations. Satisficing is thus ascribed to excessive demands. The second explanation assumes that the specific information contents made participants evaluate all solutions as equally feasible. Satisficing is thus ascribed to indifference. The third explanation assumes a more abstract effect of the information, reminding participants that the explicit costs do not sufficiently constrain choices. Satisficing is thus ascribed to an ecologically rational consideration. Based on the present data, we cannot distinguish between the explanations. Moreover, they are not mutually exclusive. For instance, combining the first and third explanation would hold that the information load of the graphic presentation shifted participants’ *weighting of explicit versus non-explicit costs*. This would resonate with findings that when quantitative information is hard to evaluate, people assign more weight to additional, non-quantitative information [27]. Future studies should disentangle the mechanisms of why more information can lead to reductionist strategies in Adapt/Exchange decisions.

While the results obtained with both numeric formats differed from graphs, they were strikingly similar to each other. Although the separate numbers required participants to integrate different information elements to compute the total solution costs, this did not manifest in different decisions than presenting the costs in an integrated manner right away. These findings contrast with intertemporal choice studies, where a segregation of numbers altered participants’ choice behaviour, e.g., [22–24]. This inconsistency could stem from the fact that segregation made the options more distinguishable in intertemporal choice, whereas it hampered their comparison in the present study. However, the findings also contrast with multi-attribute decision-making studies, where higher integration demands fostered heuristic strategies [32]. The latter inconsistency could stem from the fact that in the present study, the integration demands of the separate numbers were quite low, only requiring the addition of two values per solution. Accordingly, our presentation format with high integration demands (i.e., separate numbers) still posed lower integration demands than the formats with low integration demands that were used in previous studies.

5.2. Conceptual Questions

A number of conceptual questions should be considered when evaluating the present findings. First, our *conceptualisation of satisficing* is somewhat different from other conceptualisations used in the literature. Typically, accounts of satisficing focus on decisions between many options, e.g., [12,13,26,41], a search of large information spaces, e.g., [42,43], or non-routine problem solving under severe time constraints [14]. In these contexts, people have to eliminate options and truncate their search at some point. Conversely, in the present study, only two options (i.e., solutions) were available and satisficing was conceptualised as choosing mere adaptations of the solution when it was good enough. Thus, not all of the present findings might generalise to other instances of satisficing, and vice versa. To bridge these gaps, it would be interesting to investigate how presentation formats influence the point at which people stop searching for solutions in Adapt/Exchange scenarios. This is a relevant question in modular plants, because digital transformation allows making

previous solutions available in large databases that can be searched when a similar problem reoccurs [44]. In such case-based reasoning, the selection of suitable solutions is a major challenge [45]. Thus, it would be important to know whether more information-laden presentation formats (like the present graphs) discourage people from comparing past solutions to their current one and prompt them to truncate their search prematurely. However, it would be equally problematic if simplistic presentation formats made people restrict their focus to incomplete explicit information and neglect the broader production context.

A second conceptual question is whether people really do not compare solutions or simply *choose not to act upon this comparison*. A person might well be aware of the fact that Exchange is clearly superior in terms of its process intervention costs but then consider this irrelevant, given the negligible costs of Adapt or the large non-explicit costs of Exchange. A central advantage of humans over computers is that they can choose to ignore the data and base their judgments on information beyond what is made explicit [46]. Contradicting the assumption that participants did make the comparison but then did not enact it, a recent study traced participants' information acquisition processes in Adapt/Exchange decisions [9]. It was found that the Exchange solution was less likely to be checked when Adapt was more feasible. Moreover, the majority of participants did not check Exchange when it was clear that Adapt could be applied without any problems. Future studies should continue to specify the cognitive mechanisms underlying Adapt/Exchange decisions in order to find out at which information processing stage alternative solutions cease to be considered in different contexts.

A related conceptual question is how the two *solutions are mentally represented*. For instance, we often referred to Adapt as “staying with the status quo”, but at the same time, it could be conceptualised as “avoiding effort” or “minimising the risk of harming the plant”. These alternative perspectives differ in their focus on approach versus avoidance and thus should be subject to different biases, such as loss aversion [47], probability discounting [48], or effort discounting [49]. As different types of discounting involve different decision processes [50], it would be interesting to know how different types of framing affect Adapt/Exchange decisions. The intertemporal choice literature suggests that such framing is highly effective in changing decisions between complementary options [51]. Moreover, probability discounting is less sensitive to presentation format effects than delay discounting [52,53]. Accordingly, a more explicit framing of the Adapt and Exchange costs as risks might alter the effects of presentation format.

5.3. Limitations and Outlook

Two opposite types of limitations should be considered. The first one concerns the internal validity of our experimental setting. Perhaps most importantly, only a fraction of the information about the two solutions was *explicit and quantified*. For instance, participants learned that temperature was particularly important but were not instructed how to weight the parameters. Similarly, a large part of the Exchange costs was non-explicit. The physical effort associated with this solution could only be experienced by performing the manual Exchange procedure. Other costs were not perceivable at all but had merely been explained to participants during the instruction. As a consequence, it was unclear how costly Exchange actually was, and different participants might have had different ideas about this. On the one hand, such multidimensionality and intransparency of costs and benefits certainly reduces experimental control. The interindividual variability in our data clearly affirms this concern. On the other hand, these very features are characteristic of complex systems like modular plants. To assess how they affect people's decisions, it is inevitable to sacrifice experimental control to some extent. That said, future studies should systematically investigate the interplay between explicit and non-explicit costs. By varying the type and severity of non-explicit costs, one might assess how this changes people's information integration and strategy selection.

The second type of limitation concerns the present study's external validity. At the outset of the article, we highlighted the appropriateness of satisficing in complex

environments such as modular plants. However, the complexity of our *simplified modular plant scenario* was quite low. This scenario neither included qualitatively different risks (e.g., harming the plant, harming the product, not being finished in time) nor did it confront participants with dynamic changes (e.g., processes getting progressively destabilised, delayed effects of Adapt and Exchange). Instead, participants had to make several hundreds of simplistic decisions. This might have led to routine and fatigue effects. More importantly, it certainly is not compatible with a careful deliberation of solutions based on an integration of qualitatively different costs and benefits. Thus, it is questionable which aspects of our findings will generalise to real-world Adapt/Exchange decisions.

Another consequence of the limited complexity is that our *graph visualisations did not bring any benefits* but only made the comparison of solutions more difficult. Conversely, in real modular plants, the information provided by graphs can be essential. For instance, people should certainly know how close they are to the boundaries of a module's operating ranges or by how much a solution exceeds the acceptability thresholds. If the information contained in the graphs had been more consequential, the effects of graphs to induce satisficing might have been mitigated or even reversed. For instance, graphs could favour one or the other solution by directing attention to attributes that differentiate between the solutions, similar to presentation format effects in intertemporal choice, e.g., [18,23,54]. In this way, presentation formats might exert a wide variety of different influences on Adapt/Exchange decisions, depending on the specific information they provide.

As a third consequence of the simplistic setup, *Adapt and Exchange appeared quite similar* from a participant perspective. The qualitatively different nature of these two solutions did not become particularly transparent. Participants still seemed to take the difference between the solutions quite seriously, as discussed above: the high Exchange rate and the complex pattern of results neither are in line with a general inclination to avoid effort nor with random choice. However, this obviously does not mean that participants mentally represented Adapt and Exchange as qualitatively different solutions.

5.4. Conclusions

Choices between costly modifications and risky innovations are all but trivial in a complex world. Still, contemporary decision-making research has remained silent on how such Adapt/Exchange decisions are made. The present study contributed to bridging this gap between real-world problem structures and controlled tasks. Our results suggest that decision strategies do not only depend on the problem structure but also on the way it is presented to decision-makers. It is without question that the available information shapes decision strategies in the real world. However, it is not always clear how. A key to understanding these dependencies will lie in analysing the cognitive requirements of similar decisions in different domains [55]. For complex industrial systems like modular plants, this may require close cooperation between psychologists and engineers. In this way, psychological studies can be derived from the actual problem structures that exist out there in world. This will strengthen our understanding of how people achieve a situation-specific balance between stability and flexibility in ecologically valid decision contexts.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki. Ethical review and approval were waived for this study because the study did not involve any notable risks for participants, and in such cases, the involvement of the Institutional Review Board (or Ethics Committee) is not mandatory in Germany. We still ensured that participants were adequately informed about their rights as well as about issues of privacy and data handling. This was accomplished by using the materials for obtaining written informed consent that have been approved by our university's Institutional Review Board for use in similar studies.

Informed Consent Statement: Written informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All data are made available via the Open Science Framework: <https://osf.io/8c5mz/>.

Conflicts of Interest: The author declares no conflicts of interest.

Appendix A

The following section describes the procedure for generating the graphs, including the positions of the x, the green and purple dots, and the curves. We first defined the intended costs for Adapt and Exchange in line with Table 1 (e.g., 6 Adapt steps and 2 Exchange steps). For each combination, we then created 10 instances, corresponding to 10 trials. The integrated costs of each solution (e.g., 6 Adapt steps) could result from various combinations of temperature and mixing speed (e.g., 6 could result from 5 and 1, 4 and 2, 3 and 3, etc.). Given these values, we then manually placed the x at a random position in the small module (i.e., green box in the graph image), drew conversion and foam curves, and placed the green and purple dots above the conversion curve and below the foam curve. In doing so, the following constraints had to be met. First, the new parameter position for Adapt (i.e., green dot) still had to be within the small module's boundaries after (a) increasing the temperature and reducing the mixing speed according to the pre-defined values and (b) increasing the volume by an arbitrary amount as needed. Second, the conversion and foam curves had to be monotonically descending. This resulted from the physical constraints that higher volumes allow for lower temperature changes and lower mixing speeds require higher temperature changes. Third, the new parameter values (i.e., green and purple dots) had to be located above the conversion curve and below the foam curve. In this way, 110 unique graph images were generated (90 for relevant trials and 20 for filler trials, see main text for details). All graphs can be found in our OSF repository.

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