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Concept of a Multi-Criteria and Multi-Disciplinary Design Activity Supporting Tool in the Design and Development Process of CPS

Jerzy POKOJSKI[a] and Lech KNAP[b,1] and Stanisław SKOTNICKI[a]
[a] *Institute of Machine Design Fundamentals, Warsaw University of Technology, Poland*
[b] *Institute of Vehicles and Construction Machinery Engineering, Poland*

Abstract. The approach presented in the paper is about the concept of a multi-criteria and multi-disciplinary tool supporting design activities while designing and developing CPS. Designers who solve CPS design problems try to build computer models, and examine, verify and validate them. Usually, these models, often created ad hoc, are very complex and large and evolve in time, so the entire processes have many stages and variants. These processes come to an end after one or several sequences of selected knowledge-based activities, which in general have been modified and improved before. These activities usually concern two groups of issues: substantial and decision-making. The presented activity supporting tool concept can be applied in the design process of CPS. The main goal of the new tool is to improve the design process through more precise, effective and problem-dedicated management of the design activity models. It also enables and supports the ad hoc modelling of the collaborative integration of activities for multidisciplinarity and multi-criteria optimization analysis.

Keywords. design of CPS, multi-criteria optimization, multi-disciplinarity, transdisciplinarity, design support, industrial case

Introduction

The presented work was created as a result of the analysis of materials and retrospective threads related to a previously realized design of a control unit for selected systems of a tractor and, in particular, the tractor transmission box (TCU) [1, 2]. The control unit, under design with the tractor, is a typical CPS class system. The threads observed in the course of the project [1] and considered in the design analysis of the TCU concerned two main aspects: the observed degree of substantive correctness of the performed design activities and the intentionality and evolution of these activities in selected, strictly defined directions of the development of the entire project. The evolution of the design activities was primarily due to the shortcomings of the methods and approaches known to the designers at the beginning of the project.

Our previous works [1, 2] focused on knowledge modelling issues applied to the project under analysis. This knowledge formed the basis for the creation and

[1] Corresponding author, Mail: lech.knap@pw.edu.pl.

implementation of the design project process subjected to the presented analysis. The models created covered both the substantial-analytical side of the project and the decision-making aspects. The decision-making process was based on the modelled knowledge, but optimization techniques (mainly multi-criteria optimization) were also taken into account. The project related to the construction of the TCU, by definition, resulted in the use of models derived from various disciplines. The realized and analyzed project became the basis for creating the concept of a dedicated approach, and related tools, for designing the CPS system presented in selected aspects in this paper.

1. Engineering knowledge modelling

The problems of capturing, storing and reusing engineering design knowledge have been the subject of very intensive research and development over the past 30 years [7, 8]. The following facts have contributed to this: the increase in the complexity of the implemented design tasks [9, 10], the attempt to reduce product development time and increase the quality of the product itself, functioning in a distributed environment [11], as well as a significant increase in the awareness of the role of knowledge in engineering processes and the necessity of its storage, maintenance and sharing [12-14]. Nowadays, additionally to the substantial knowledge [13, 14], the broader context and its long term development [15,16] are considered more often. For CPS projects the aforementioned issues are particularly important due to their scale and the high degree of multifacetedness and complexity of the problems being solved [3, 17, 18].

The presented approach attempts to integrate the concept of knowledge-based software [7, 8] with multi-criteria optimization applied to a multidisciplinary problem [3, 19]. Particular emphasis has been placed on the issue of flexible, knowledge-based, interactive management of a multi-stage evolutionary problem-solving procedure and its main functionalities [20, 21].

With CPS optimization tasks, at the initial stage of the task modelling process, or sub-tasks [4, 5] of multi-criteria optimization, it is difficult to unambiguously determine and predict the final areas/sub-areas, ranges and sizes of individual tasks that are to become analyzed models (which are the basis for final decisions). Analysis, experimentation on a large scale, and the selection of methods are necessary as tool modules have to be integrated. This is a rather labour-intensive stage.

In general, multidisciplinary CPS models are relatively large and complex [4, 5, 17, 18]. They are assemblies of partial models [23-26]. The interrelationships of partial models reflect the fact that products and their design problems are extended structures which are homogeneous and multifaceted. They are also based on knowledge from different disciplines.

The subject matter knowledge and individual preferences of designers determine which models, and at what level of model accuracy, will be used in a given case. This knowledge should be acquired, stored, and reused [1, 2, 12].

2. Modelling multidisciplinary design tasks

Machine design engineers create mental, mathematical, and computer models [9, 10]. They study them, analyze them, and use them for simulation. The next steps are the use, verification, possible modification and natural validation of the models [13, 14]. These activities are based on specific engineering knowledge resources.

It has to be noted that all these steps are accompanied by the intensive mental work of the designers aiming to build a design process composed of specific design activities based on related tools [1, 2]. As a result, each of the design activities [2] considered as necessary is implemented at a specific, preconceived level of model accuracy - initially in a more general form and in subsequent iterations in a more tailored, sometimes more detailed form.

Activities evolve as knowledge advances and develops [1, 2, 13, 14] during the design process. They are adapted to changing circumstances. Their functioning changes and their associated tools evolve [13, 14]. The problems of this class modelled today has to concentrate on storing and analyzing broad contexts of the applied knowledge [15, 16].

Usually, for each designer and his/her specific area of professional competence, a whole class of models can be built. They consist of design activities and their tools, which, remaining with each other in specific relations, give the possibility of articulating sets of plan-models for realizable design processes [8, 13, 14]. At the same time, relationships can take a "soft" form, i.a. inequalities between attribute values, mappings of a point into a set, etc. They can also take a very formal form of variables called coordination variables [12, 19] that bind together well-defined subproblems (an approach known from multidisciplinary optimization).

2.1. Classical design and elements of CPS design

Nowadays, the design processes of systems in which CPS occurs are generally largely composed of elements typical for classical design processes. They contain in many cases only a few fragments typical for CPS [1, 2]. Designers are usually cautious, approach the design of CPS elements with restraint and reserve, and observe and analyze all steps carefully. Usually, when designers start work with projects that also include CPS they do so in little steps. They are rather far from carefully building precise, complex models and approaches.

When it is possible, designers often design CPS systems mentally, as they usually do in classical design. CPS design, at least in the first iteration, is done in multiple stages. It is a standard process to which various new elements are added. Attempts to create these new elements are accompanied by integration efforts. It is important to obtain initial guiding answers to various questions. Basic ideas emerge and attempts are made to apply them. In general, this means the complexity of the basic models. The taken actions are to test a variety of basic new ideas, which usually boil down to evaluating their sensibility and assessing the rationality of raising the complexity of the models themselves. At this stage, usually no expensive and detailed models are built. Everything is based on relatively simple models or also relatively simple modifications of them.

An effective method of solving the problem in this case may be to use the relatively simple concept of modelling a multi-attribute decision-making task [8]. Then the problem is reduced to generating a set of design solution variants, where each of them has certain attributes (generally captured numerically). Some of these attributes can become criteria that may be used to extract a set of Pareto optimal solutions and further to select the single most preferred solution. In such a complex process - as even the simplest design of structures with CPS elements - it happens that more single tasks of multi-attribute decision-making occur which can also be solved in the way described above [8]. Often, formal relationships between such tasks, which are sometimes called sub-tasks, are not taken into account. However, there are cases where these links between sub-tasks cannot be ignored. The variables that bind the sub-tasks are called coordination variables. Their choice determines the trade-off in solving any of the sub-tasks. It is also possible to construct a global task, whose criteria depend both on individual sub-tasks and their mutual relations expressed in the choice of coordination variables. Further possibilities of this approach are modelling preferences for favouring any of the sub-tasks or the global task, or working out a compromise between these tasks. A hierarchical order approach can also be used for this purpose [8].

The above proposal, which solves a complex multi-discipline, multi-criteria optimization task by using approaches typical of multi-attribute decision making, has the advantage of being relatively simple, making easier an understanding of a not very extensive conceptual layer: variants-attributes, criteria, optimality in the Pareto sense, hierarchical order, related tasks. The functional side of this somehow limited class of approaches is not very complex either.

At the conceptual stage design problems with CPS elements are mostly not described by advanced formal models. Instead, they are very often models from different disciplines - we speak of their inter- and transdisciplinarity, and they rarely have any prior development behind them. But in this case a relatively simple optimization approach based on multi-attribute (as opposed to multi-objective) relatively good yields results in further refining the previously studied models in a clear way.

The above proposal can be directly related to the concept of project activity modelling, where the sub-tasks are tasks associated with a specific project activity and its specific development version [1, 2]. General tasks – mean working out the trade-offs between sub-tasks and global tasks, and also modelling the relationships between specific instances of project activities, and as a result optimization in a broader sense. Important in all this is the ability to quickly create and analyze this class of models.

The authors based their concept on relatively simple computer programs that have functions generating sets of variants, and functions allowing the selection of solutions in the Pareto sense, and solutions based on the hierarchic order. Furthermore, they allow a relatively simple integration of sub-tasks, and then processes of preferred optimal tasks selection can be performed.

3. Test use of the proposed approach in an example CPS design case

Returning to the concepts of CPS systems, we can state that the concepts presented in the previous chapter are relatively easy to implement for the designer. They gradually develop and may become a widely available tool for testing hypotheses created and modified by the designer.

Let us turn to a concrete example of modelling selected subproblems in the task of building an electronic control system for the operation of the main transmission system of a tractor as well as other supporting systems:

1. We consider the project activity: designing the part of the electronic controller which is responsible for the hydraulic valves control - which provides the definition of the characteristics of the system under study. The activity is based on the authors' personal knowledge and the mathematical models which they gained and created in previous similar projects. While implementing the

knowledge, a whole range of resultant quantities are generated, including the hydraulic valve current characteristic. The characteristics of such relationships are shown in Fig. 1. The right side of the figure shows selected design quantities identified as key elements. These quantities are used both in the physical layer (hardware) and in the built numerical models to assess the correctness of the operation of a given version of the design. The performance of an electronic system is also affected by the number and type of sensors and actuators needed in other design activities. For example, too high a temperature of the electronic system or too many connected devices with an available power source can cause the inadequate operation of electronic system components (e.g., too low voltage or current). Consequently, an improper operation of sensors and actuators can be observed which influences the whole CPS system. So, it is possible and necessary to construct a multi-attribute decision-making task for such a problem, to which various specific methods for its solution can be applied [12, 19]. Ultimately, one can choose a single optimal solution in the Pareto sense.

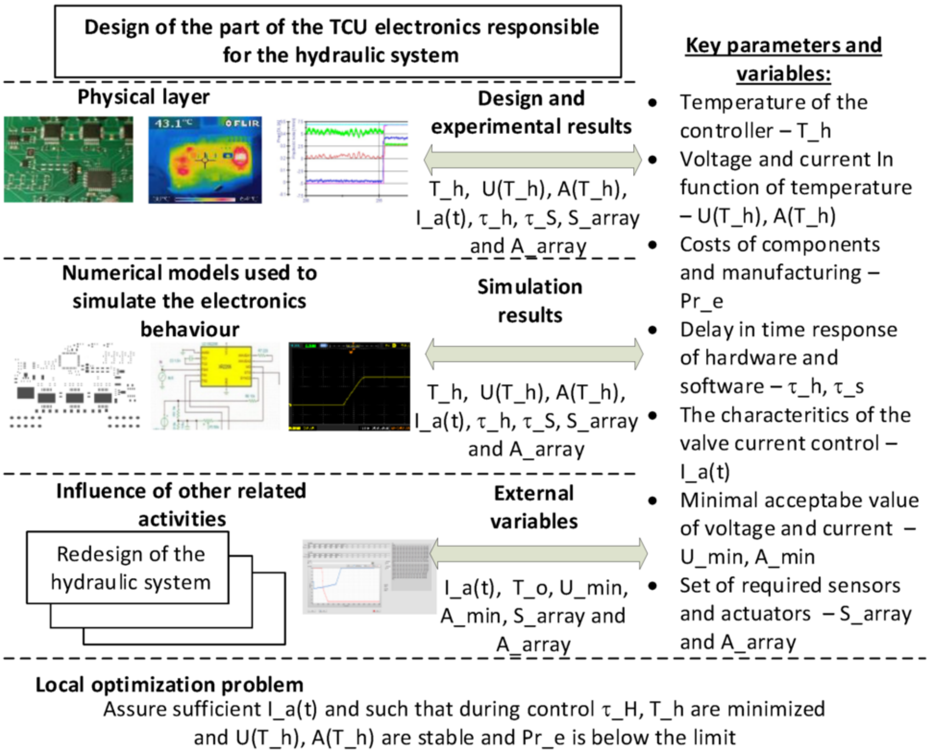

Figure 1. The design of the electronic controller responsible for hydraulic valves control.

We also present a second example of a design activity (which generally involves a different discipline): the redesign of a hydraulic system. The example is based on other models, leads to a better definition of the characteristics of the hydraulic system, and redefines the requirements for the current characteristics of the hydraulic valve controlling the operation of the clutches of each gear. However, at some stages, one of the quantities generated in 1) should be related to the set of quantities present in 2).

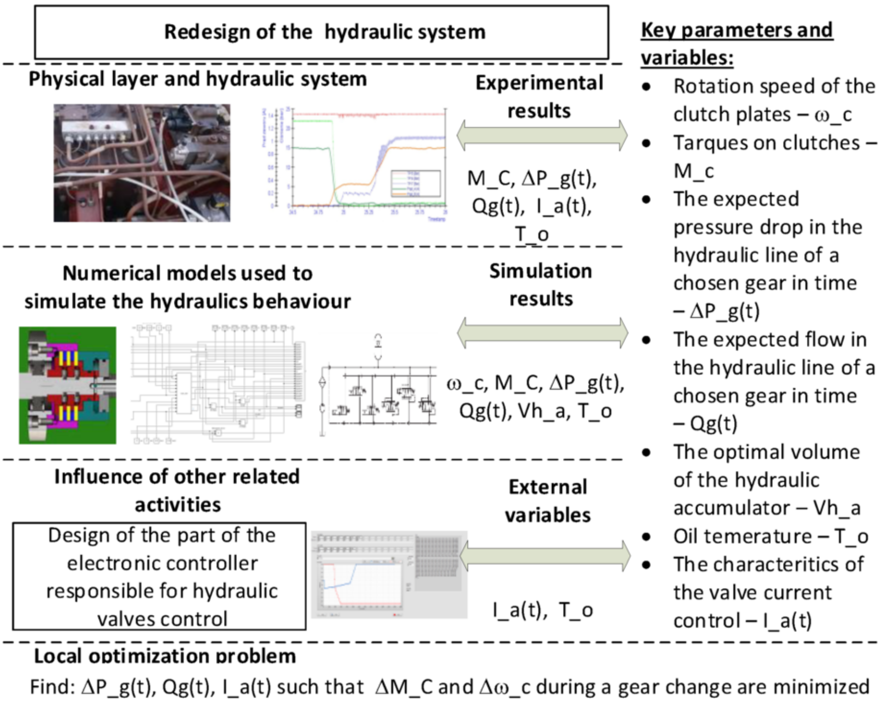

Figure 2. Redesign of hydraulic system.

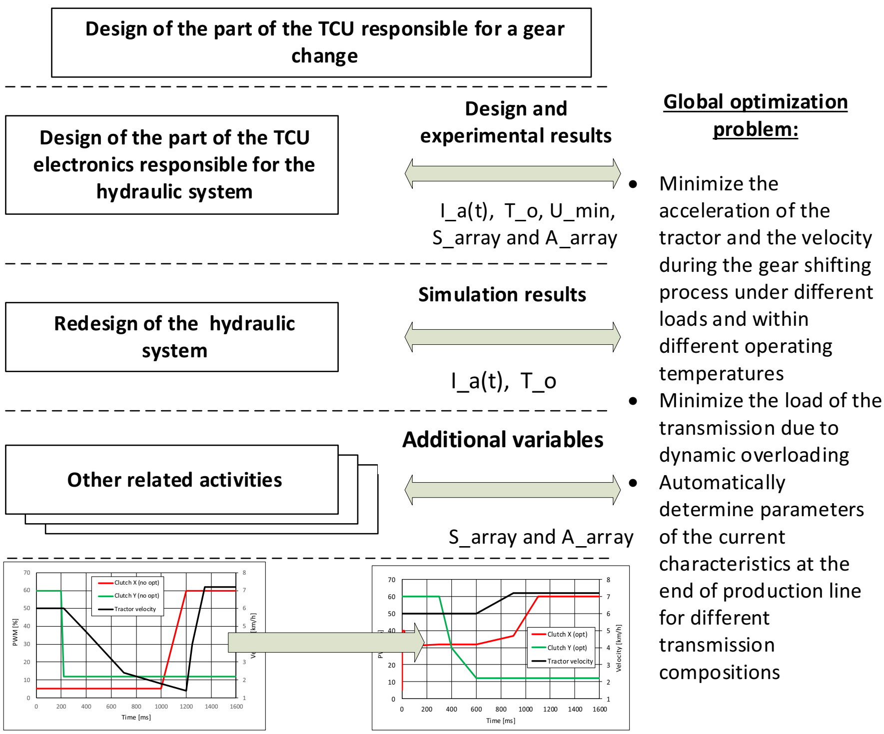

Figure 3. Activity links in the controller design process.

The functioning of this activity, and the conditions for the functioning of such a link, are shown in Fig. 2. On the right side of the figure the key quantities for the activity and the correct operation of the hydraulic system are shown. These quantities have a key effect on the gear shifting process. For example, one of the quantities I_a, which is also shown in Fig. 1, is the change over time of the current supplying the valve responsible for the operation of the multi-plate clutch hydraulic cylinder. The time-dependent actuation of the hydraulic cylinder affects local quantities such as pressure drop (ΔP_g), clutch plate speeds (ω_c), clutch torque transmission values (M_c), but also clutch plate friction lining wear and servicing costs. In this case, a multi-attribute decision-making task can also be modelled, to which various specific methods can be applied to solve it [3, 12, 19]. And, as before, the solutions obtained are optimal in the Pareto sense.

2. It is possible to link both activities, build a new complex task, and do an appropriate analysis, including multi-attribute. Integration tools are needed for this. The tools may be general purpose, but it is desirable that they provide automatic, fast and simple ad hoc integration. The structure of this class is shown in Fig. 3. Based on this structure, we are able to model the related tasks 1 and 2 as sub-problems of the global multi-criteria optimization task. The multi-attribute approach can also be used in this case. The procedure characterized above can be continued with successive sub-models of successive activities [1, 2, 20-26]. New consecutive links that make real sense can be created. The result is a map of the various integrated sub-models together with locally derived analysis and optimization results. The obtained picture shows the estimated potential of the perceived and applied model structures and allows us to find connections and influences between individual local analyses.

The whole procedure presented above leads to the extraction from a very large set of potentially integrated models those which are needed, which are promising and have innovative potential, and probably a decisive influence on the outcome of the design process.

4. The concept of a staged building of the software environment to support the CPS design process

Some example formal models of such integrated sub-problem structures tend to have application areas with a well-established history of their development. These include, for example, the aerospace industry [3, 19]. However, it is much more difficult to build this class of structures for tasks not previously solved by this class of methods.

A particularly vast search space is likely to occur for CPS systems [4-6, 26, 27]. An effective solution in this case may be a stepwise, evolutionary analysis of different types of relationships between, for example, two selected different design activities and their tools. The relationships may be relatively simple, e.g. linking a single variable in one activity to a set of variables in another activity. In addition, such a relationship can be unidirectional: first, one activity is implemented, and the results of its implementation are transferred mathematically, formally to another dependent and implemented activity. It is also possible to indicate which variables had a decisive role in the successful implementation of a given version of the activity.

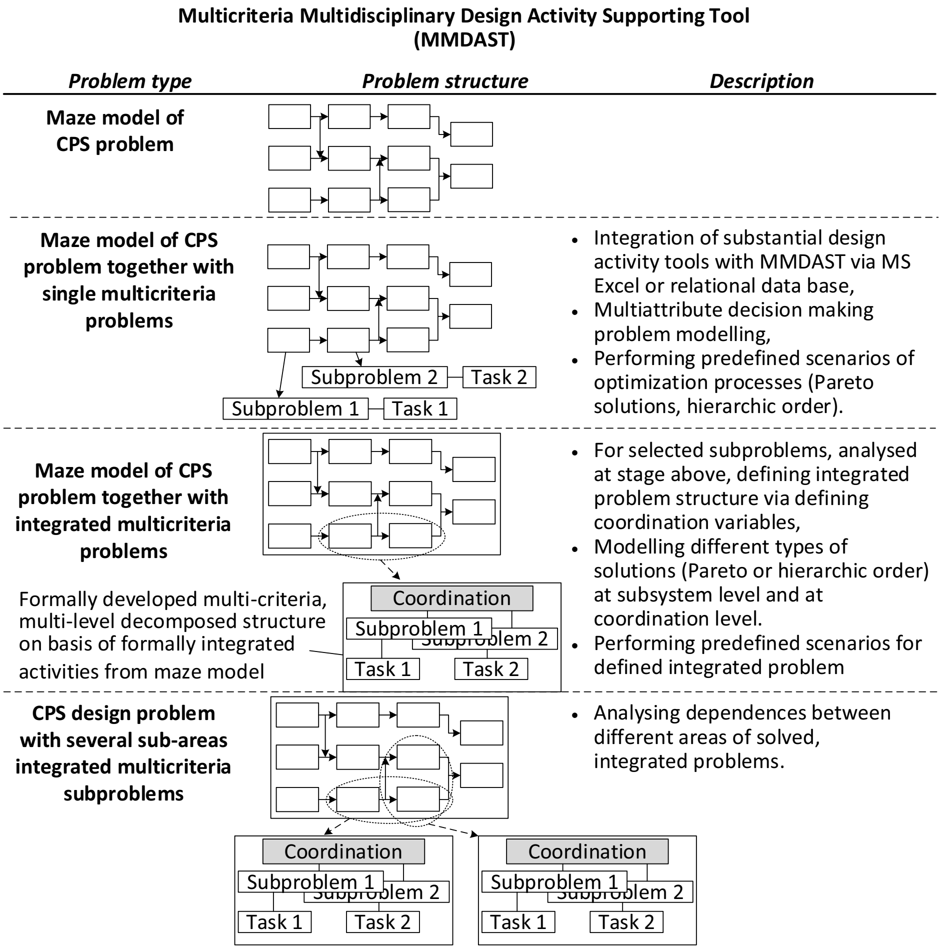

Figure 4. Architecture of the Multicriteria Multidisciplinary Design Activity Supporting Tool (MMDAST).

It is, of course, possible to analyze different types and directions of such relationships. It is also possible to impose various formal requirements on the results obtained this way, e.g. the attainability of certain preset thresholds of certain variables and functions, or the search for the largest value of some of them, or the search for the realization of a trade-off between them. All this constitutes a certain initial modelling potential of the discussed approach.

The authors propose an evolutionary strategy (c.f. Fig. 4): first to set basic hypotheses for modelling integrated tasks consisting of 2-3 problems, and then analyze them and make subsequent attempts at modelling and analysis. The approach involves a gradual refinement of the design process and the activity in it through the designer's recognition and learning of the problem. After that, mainly based on mental processing and reflection, he determines the next steps in modelling and analysis/optimization. This concept refers to processes usually performed by designers. However, it assumes making the development of design activities, the knowledge acquisition and the modelling tasks integrated from sub-tasks more efficient. The main assignment of the designer is to interactively control the development and model expansion, depending on the needs necessary to solve a given problem at a given time.

The authors also plan to develop a set of standard patterns - scenarios of operating with the proposed system.

In general, the main goal of the proposed approach is to make fast and economically rational analysis of multi-criteria decision tasks which are qualitative, multi-disciplinary, and can be modelled locally ad hoc.

Of course, large systems [3] for this class of tasks are available. However, using them is labour intensive. Expertise is required in both decision problem modelling and system decomposition, in framework integration, optimization task modelling, and optimization execution processes. This means the first valuable results appear after a lot of work in the preliminary stage.

The authors have already developed various limited implementations based on the presented concepts (chapter 9 in [8]). They have also developed concepts with probabilistically modelled elements. The authors plan to build a series of independent applications supporting different classes of decision problems with predefined task structures. Over time, it may prove effective to integrate them and transfer the complex task thus built to a system designed to solve large multidisciplinary tasks of this class.

5. Conclusion

The approach proposed in this paper attempts to make typical designers' work more efficient when they solve problems that are not fully known in a meaningful way. Usually, the engineers undertake model modifications, directed model modifications, based on knowledge, experiments and simulations. These are directions of the environment development based on the knowledge gained and the evolutionary exploration and learning of its requirements.

Each of these activities also contains a lot of manual, repetitive actions that should be gradually automated to increase the effectiveness of the entire environment. These activities include the automation of integration processes as well as the improved predefinition of decision tasks and optimization tasks. The authors' aim at both directions.

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