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Operational Design Co-ordination: An Agent-Based Approach

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SYNOPSIS

Operational design co-ordination has been identified as the basis for an approach to engineering design management that is more comprehensive than those that currently exist. As such, an integrated and holistic approach to operational design co-ordination has been developed that enables design to be managed in a coherent, appropriate and timely manner. Furthermore, the approach has been implemented within an agent-based software system, called the Design Co-ordination System, which has been applied to an industrial case study involving the computational design analysis of turbine blades. This application demonstrates that managing and adjusting in real-time in an operationally co-ordinated manner enables reductions in the time taken to complete the turbine blade design process to be achieved.

1 INTRODUCTION

Engineering design is challenging from both a technical and management perspective. With regard to management, the design development process of large made-to-order products can be complex, expensive and time-consuming due to the involvement of many resources and tasks, and large quantities of data, information and knowledge. As such, engineering organisations are becoming increasingly aware that effective and efficient operational design management can significantly influence the success in bringing high quality products to market in less time and at reduced cost. Consequently, there is a requirement for a methodical and well-organised approach to design management.

Operational design co-ordination has been identified as the basis for a more comprehensive approach to design management than those that exist. The key elements of operational design co-ordination in a real-time environment have been established as coherence, communication, task management, dynamic schedule management and resource management (1). Thus, a holistic approach has been developed that integrates the elements named such that design can be managed in an appropriate and timely manner. That is, coherently enabling multiple inter-related tasks to be undertaken and completed by allocating and utilising multiple resources, of varying performance efficiency, in an optimised fashion in accordance with multiple dynamically generated schedules in real-time within a changeable and unpredictable design development process. Furthermore, the approach has been implemented within an agent-based software system, called the Design Co-ordination System. This multi-agent system has been applied to an industrial case study provided by the power generation industry involving the computational design analysis of turbine blades.

2 OPERATIONAL DESIGN CO-ORDINATION

The latter part of the 20th century has seen the introduction of an increasing number of management initiatives aimed at improving the competitiveness of organisations. Engineering design has seen the development of a range of approaches to various management initiatives that have been implemented within industry such as concurrent engineering, workflow management and computer supported co-operative work. Within these and other initiatives, co-ordination has been observed as an important and pervasive characteristic (1). However, despite being widely cited, the understanding conveyed regarding co-ordination varies considerably. In addition to engineering design, co-ordination has been identified as a key research area in distributed artificial intelligence and organisational theory. Thus, in order to develop a truly co-ordinated approach, each of the characteristics of operational co-ordination recognised within these disciplines must be integrated within a unified approach.

2.1 Coherence

"Engineering design problems are often solved by a group of individual participants with different expertise, loosely organised as a design team" (2). As such, it was recognised that participant's activities must be co-ordinated in order to maintain coherence. Similarly, the co-ordination problem has been viewed as "how a group of people organise themselves to work as a coherent team in order to accomplish some task" (3). In addition, co-ordination has been described as "a process in which agents engage in order to ensure their community acts in a coherent manner, i.e. agent actions gel well and do not cause conflict with one another" (4).

2.2 Communication

It has been stated that "coordination is brought about by communication" (5) and "communication is the basic means of coordination" (6). Further, it has been indicated that co-ordination is the interaction among a set of agents performing some collective action (7). More specifically, "communication enables the agents in a multi-agent system to exchange information on the basis of which they co-ordinate their actions and co-operate with each other" (8).

2.3 Task Management

Co-ordination has been viewed as "steering and integrating activities" (9) and "the division and management of activities" (10). Moreover, the control of activities has been described as being central to design co-ordination (11). In addition, it has been stated that "co-ordination requires activities to be carried out in an orderly fashion" (12) and "design co-ordination is aimed at structuring activities in such a fashion to achieve optimal performance" (13). Related to structuring activities, co-ordination has been defined as "the process of managing dependencies between activities" (14). This definition has been influential in the areas of distributed artificial intelligence and organisational theory. For example, it has been indicated that co-ordination of agent activities becomes necessary when there are interdependencies between them (15), and that "co-ordination problems are primarily concerned with dependencies between the activities performed by system entities" (16).

2.4 Dynamic Schedule Management

The co-ordination of engineering design has been defined as "assigning particular tasks to individuals or groups" (17). Further, the assignment of tasks to processors, or scheduling, has been described as one of the fundamental components of co-ordination (18,19). Scheduling is viewed as the assignment of resources and start and end times to tasks (20). However, it was also indicated that schedules are not truly effective unless they are properly monitored and controlled. The need to modify planning decisions is required since the design process can change and certain planning decisions can only be made as a result of the completion of particular stages of the design process (21). As such, it is recognised that there is a requirement to change, in real-time, the planned schedules of resources (22).

2.5 Resource Management

Design co-ordination has been described as covering aspects of the organisation, management and control of resources (23). In addition, "the focus for supporting design co-ordination is directed at the effective utilisation and integration of resources in order to optimise design activity" (20). Similarly, with regard to design co-ordination, the allocation of resources has been identified as an important task within design management (24).

The use of many resources to facilitate the efficient performance of activities is an approach that has been reported as having benefits such as speeding up a process (19). However, it has been reported that committing greater resources to a problem does not necessarily result in a proportional reduction of time to complete tasks (25). Rather, "it is the capacity to co-ordinate the activity performed by each team member, taking into account the available resources and knowledge of their roles and effects, that enables a measured reduction in the duration of those activities to be achieved".

3 AN AGENT-BASED APPROACH: THE DESIGN CO-ORDINATION SYSTEM

The Design Co-ordination System (DCS) is an agent-based system aimed at operational design co-ordination of a computational design analysis in real-time. The agent paradigm has been adopted within the DCS since agents are analogous to individual engineers within an organisation (26). In addition, the characteristics of a multi-agent system (MAS) correspond with those of an engineering organisation (27). That is, engineers are unable to perform all of the work themselves, no individual has complete organisational control, and knowledge and information is distributed throughout the organisation.

Within the DCS, the agents act as members of a multi-functional team operating in a co-ordinated fashion. As shown in Figure 1, seven different agent types are used.

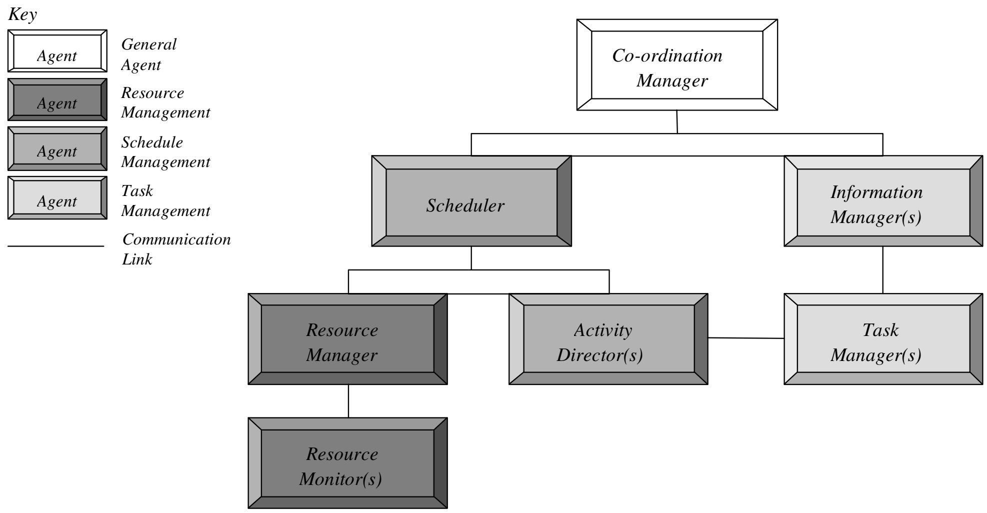

Fig. 1 Design Co-ordination System Agents

Within any application of the DCS, the number of agents of type Co-ordination Manager, Resource Manager and Scheduler is fixed at one. The number of agents of type Information Manager, Task Manager, Resource Monitor and Activity Director is dependent on the number of analysis tools to be used in the computational design analysis and/or the number of available resources in the computer network environment. An analysis tool is an individual software module that is executed, which uses input to produce corresponding output. Each execution of an analysis tool uses different input information, and is defined as a task within the context of the DCS. A resource is a machine in the computer network environment on which analysis tools can be executed.

At the outset of the operation of the DCS, the Co-ordination Manager facilitates communication links between related agents that need to interact. Once all appropriate agents are introduced, the Scheduler invokes a multi-objective genetic algorithm (MOGA) (28) to derive a schedule from which the original schedule models are based. These schedule models enable the optimised utilisation of the resources with respect to the outstanding tasks. Activity Directors orchestrate Task Managers in accordance with their respective original schedule models such that their designated tasks can be completed. Task Managers operate such that prior to executing their tasks, the appropriate task input information is requested from their related Information Manager. Task Managers complete their tasks and inform their related Activity Director and Information Manager, which stores the resulting task output information. Activity Directors inform the Scheduler as tasks are completed and when they have concluded their original/revised schedule models. Throughout the computational design analysis, Resource Monitors observe and analyse the monitored performance efficiency of their associated resource and inform the Resource Manager of any significant change. The Resource Manager is responsible for ensuring that knowledge of resources is maintained at all times and informing the Scheduler if a new schedule may be required. On instruction from the Resource Manager, and if appropriate, the Scheduler invokes the MOGA in order to derive revised schedule models. The process of determining whether or not re-scheduling is appropriate involves consideration of future expected performance of resources, outstanding tasks and the performance characteristics of the MOGA. In addition, if re-scheduling is performed, interim schedule models are derived and adhered to such that best use is made of the resources during this period.

4 INDUSTRIAL CASE STUDY

A case study was provided by industry to enable the application of the agent-based approach to operational design co-ordination through the Design Co-ordination System. The case study involves a suite of analysis tools that the designers use in the turbine blade design process. Use of the analysis tools enables the thermodynamic and mechanical design of turbine blades within prescribed boundaries to give optimum thermodynamic efficiency and mechanical integrity. That is, the analysis tools are used in the selection of blades and the calculation of the associated stresses and vibration characteristics of the blades to meet the criteria stated. The deterministic analysis tools are related as shown in Figure 2.

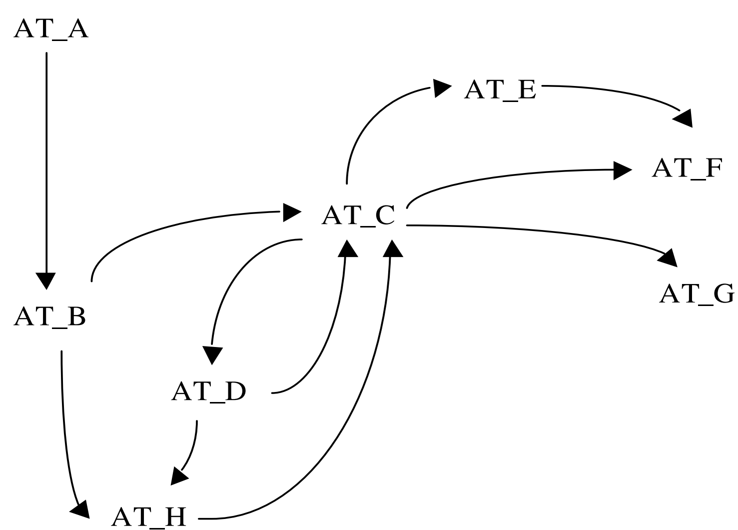

Fig. 2 Turbine Blade Design Process: Analysis Tools

In total, 131 tasks, i.e. analysis tool executions, are to be undertaken involving the single execution of some analysis tools and multiple executions of others.

On instantiation of the DCS, the appropriate agents are created. That is, a single Co-ordination Manager, Resource Manager and Scheduler are created. In this case study eight analysis tools and four resources are used. Thus, eight Information Managers are created, thirty-two Task Managers, four Resource Monitors and four Activity Directors. Initially, the Co-ordination Manager receives messages from all other agents, which are then registered. On acknowledgement of their registration, agents request knowledge regarding related agents from the Co-ordination Manager. Once this knowledge is supplied, related agents can then communicate directly with one another when required.

Prior to the start of the computational design analysis, the designer provides knowledge of the (i) tasks to be completed, i.e. executions of analysis tools, and (ii) resources to be utilised, i.e. machines to be used. Based on this knowledge, the Scheduler constructs a task model, which holds knowledge attributes for each task such that they can be undertaken in a structured manner, while preserving the relationships between them. In addition, the Resource Manager constructs a resource model, which contains knowledge of the performance attributes of each of the four resources such that they can be utilised in an optimised manner.

4.1 Derive an Optimised Schedule

At the beginning of the turbine blade design process, all tasks need to be scheduled. The Scheduler prepares task and resource knowledge, from their respective models, required for use with the MOGA. On execution of the MOGA, a Pareto optimal set of schedules is created. The *best* schedule is selected from this set based on three decision-making criteria, i.e. minimise (i) time, (ii) number of resources, and (iii) resource utilisation.

4.2 Construct Original Schedule Models

The Scheduler uses the *best* optimised schedule to construct an original schedule model for each resource to be utilised. The responsibility of administering the enactment of each original schedule model lies with the Activity Director of the corresponding resource. Thus, the Scheduler provides each Activity Director with their respective original schedule model.

4.3 Check Dependencies, Direct and Undertake/Complete Tasks

On being provided their original schedule models, each Activity Director begins administering the designated tasks to be undertaken. During the direction, undertaking and completion of tasks, Activity Directors, Task Managers and Information Managers work simultaneously in a coherent manner.

On inspecting its associated original schedule model, one Activity Director recognises that its first task, i.e. the execution of *AT_B*, is dependent on the execution of *AT_A*. This dependency exists since *AT_B* requires the output file produced on executing *AT_A*. Thus, the Activity Director confers with the Scheduler in order to establish if the task dependent on has been completed. On checking the task model, the Scheduler observes that the execution of *AT_A* has not been completed and, as such, the execution of *AT_B* cannot commence. Further, the Scheduler records within the pending scheduled task repository that *AT_B* is awaiting *AT_A*. Similarly, the first tasks of the Activity Director associated with each of the other two resources cannot commence since they require information that will only be made available on the completion of *AT_B*. Once the Activity Director responsible for overseeing the execution of *AT_A* has been informed that it may commence, it instructs the related Task Manager to undertake and complete the task.

4.4 Request, Provide and Supply Task Information

Prior to executing *AT_A*, the relevant Task Manager requests that its related Information Manager provide necessary input information. In response, the Information Manager retrieves the input file from the task information repository. On notification that the requested information has been provided, the Task Manager commences with the execution of *AT_A*. Once *AT_A* has been executed, the Task Manager informs its related Information Manager such that the output files produced can be stored in the task information repository. Thus, these files are readily available in the event of them being required as input for the execution of other analysis tools, specifically, at this time in the process, the pending scheduled task involving the execution of *AT_B*.

4.5 Update Task Model

On completion of the task involving the execution of *AT_A*, the Task Manager informs its related Activity Director, which then informs the Scheduler. The Scheduler updates the task model to reflect the completion of the task. Updating the task model in this manner ensures that in the event of re-scheduling, only outstanding tasks are considered.

4.6 Remove Dependencies and Commence Direction of Pending Scheduled Tasks

In addition to updating the task model, the Scheduler updates the pending scheduled task repository such that any tasks solely awaiting the completion of the task just completed may be undertaken. Specifically, since the execution of *AT_A* has completed, the Scheduler removes this dependency from the pending scheduled task repository. Consequently, the task involving the execution of *AT_B* can be undertaken. The commencement of this task is instigated by the Scheduler who informs the appropriate Activity Director.

4.7 Monitor Resources

Throughout the operation of the DCS, each Resource Monitor observes the various constituents of usage of their associated resource at 5 second intervals. Based on these observations, each Resource Monitor determines the monitored performance efficiency at corresponding time intervals such that any significant deviation exceeding specified thresholds can be identified. Figure 3 represents the monitored performance efficiency for the four resources utilised during the turbine blade design process as observed by their associated Resource Monitors.

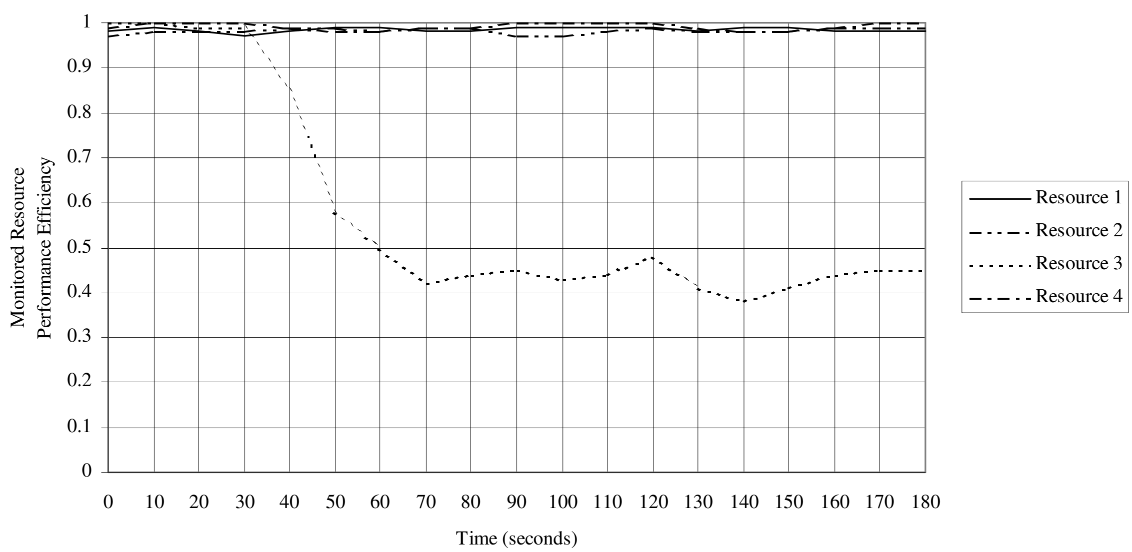

Fig. 3 Monitored Resource Performance Efficiency versus Time

In Figure 3, at approximately 60 seconds there is a deviation in monitored performance efficiency for resource 3 that exceeds its lower threshold of 0.5, which initiates the consideration of re-scheduling. Further, the monitored performance efficiency fluctuates between 0.38 and 0.48 thereafter. For the other resources, monitored performance efficiency is approximately 0.99 throughout the operation of the DCS.

4.8 Forecast and Revise Resource Model

Due to the lower threshold of resource 3 being exceeded, the associated Resource Monitor forecasts future performance efficiency by performing a regression analysis using orthogonal polynomials. The Resource Monitor predicts future performance efficiency to be 0.418, which is supplied to the Resource Manager such that the resource model can be updated. The Resource Manager then requests that the other Resource Monitors determine and report forecasts of performance efficiency. Once reported, the resource model is updated to reflect these forecasts. Further, the Resource Manager instructs the Scheduler to consider re-scheduling based on the new forecasts of performance efficiency held in the resource model.

4.9 Decision Making for Re-Scheduling / Derive and Enact Interim Schedule Models

In order to establish if re-scheduling is required, the Scheduler assesses whether it is more economical time-wise to continue with the current schedule or, alternatively, re-schedule a proportion of the outstanding tasks and complete the revised schedule. During the period of re-scheduling the remainder of outstanding tasks would be able to be completed in accordance with the interim schedule models.

In order to make the decision whether or not to re-schedule, the Scheduler determines estimated times to: (i) complete the current schedule, (ii) derive a revised schedule and (iii) complete a revised schedule. An estimate of the duration to complete the current schedule is obtained by each Activity Director by dividing the cumulative datum duration of the outstanding tasks by the forecasted performance efficiency of their associated resource. The Activity Director that reports the greatest duration is taken as the time to complete the current schedule. The Scheduler determines the estimated time to derive a revised schedule based on an empirical study of the MOGA, which accounts for the number of tasks to re-schedule and the dependencies between them. The Scheduler also calculates the estimated time to complete a revised schedule by grouping tasks according to their relationships and then determining the critical path while accounting for the performance efficiency of the resources to be utilised.

An estimated time to continue the current schedule was calculated as approximately 79 seconds. Performing re-scheduling, while simultaneously completing interim schedule models, and the time to complete the revised schedule was estimated as approximately 38 seconds, i.e. 20 + 18 seconds. Thus, the Scheduler takes the decision to re-schedule.

4.10 Completion of the Turbine Blade Design Process

Once re-scheduling has been performed and, simultaneously, the interim schedule models are completed, the revised schedule models are derived. The turbine blade design process then progresses until all tasks have been completed according to the revised schedule models.

5 DISCUSSION AND CONCLUSIONS

The case study has demonstrated the approach to operational design co-ordination in real-time by applying the DCS. Throughout the turbine blade design process, all agents communicated and interacted in a coherent manner such that inter-related tasks were undertaken in the right order, by the appropriate agent, using the right information and utilising the right resource at the right time. Further, the application of the DCS has been shown to support the continuous optimised utilisation of resources. This is achieved by monitoring resources and, if appropriate, adjusting their utilisation according to predictions of future performance. Tasks are managed such that they can be undertaken and completed in a structured manner. This is enabled by continuously managing and maintaining knowledge and information associated with tasks. Based on knowledge of tasks and resources, the DCS has been shown to support the dynamic derivation of suitable schedules, at appropriate times during the turbine blade design process, and their enactment.

In addition to performing the process in a co-ordinated manner, a key feature of the approach is that by adjusting in real-time if and when appropriate, benefits can be made in terms of reducing the time to complete the process. However, the magnitude of any reductions that can be achieved are dependent on the stage of completion of the turbine blade design process. With regard to the case study, by deciding to re-schedule, the process was completed in approximately 38 seconds from the point in time when re-scheduling was considered whereas continuing to adhere to the original schedule models would have taken 79 seconds. As such, from the point at which re-scheduling was considered, an approximate reduction of 50% in time to complete the turbine blade design process was achieved.

In the case study, relatively significant reductions in the time to complete the turbine blade design process have been achieved as a result of applying operational design co-ordination in real-time. In order to demonstrate the approach further in terms of scalability, future work will involve the application of the approach within an engineering organisation where similar significant savings in time could be achieved on a larger absolute scale, i.e. in the order of man weeks or man months.

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