Engineering management: operational design coordination

GRAHAM COATES†*, ALEX H. B. DUFFY‡,
IAN WHITFIELD‡ and WILLIAM HILLS†

Effective engineering management is acknowledged as being fundamental to the successful operation of organizations. While traditional and contemporary approaches to operational engineering management are of great significance, there remains a need to make further advances in this field. Such advances will enable an increase in the competitiveness of an organization by contributing toward delivering quality products in shorter timescales at an acceptable cost. As such, there is a requirement for a more comprehensive and innovative approach that offers a means of improving the operational management of engineering. Existing approaches recognize coordination as an important and pervasive characteristic of operational engineering management; however, they fail to offer a consistent understanding and appreciation of the concept. This paper comprehensively identifies the key elements of operational design coordination, which will provide the basis for an improved approach to engineering management.

1. Introduction

Management has been considered as consisting of a strategic level and an operational level (Greenley 1989, Cole 1994). Finlay (2000) identified that an organization comprises a strategic apex to oversee the whole of the business, and an operational core described as the people who perform the basic, day-to-day processes. Greenley (1989) described strategic management as providing a framework for operational management, which was defined as being concerned with the efficient use of the existing production capacity. Similarly, Cole (1994) described the relationship between the two levels by stating that 'strategic management produces the primary goals and framework within which they can be realised for operational management'. Furthermore, it was indicated that the concerns of strategy were effectiveness (i.e. ensuring that the organization is doing the right thing) whereas the concerns of operations were efficiency (i.e. doing things right). This paper focuses on the operational level of management.

The operational management of large made-to-order engineering 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. The complexity is compounded by the fact that resources are often skilled in a variety of disciplines and exhibit varying proficiency regarding the completion of multiple inter-related tasks. Furthermore, due to unforeseen circumstances, resources may not perform as intended and/or scheduled tasks may not progress as expected, the outcome of which will influence the performance of the design development process. A methodical and well-organized design development process lies at the heart of an effective engineering company since it can enable the reduction of development costs and cycles while meeting customer quality requirements. Thus, to remain competitive, new approaches to managing the design development process are needed to ensure effective and efficient processes (i.e. strategically to do the right things and operationally to do things right).

The aim of this paper is twofold. First, coordination is revealed to be an important and pervasive characteristic of existing approaches to operational engineering management. Second, the key elements of operational design coordination are identified that provide the foundation for a more comprehensive approach than those existing.

2. Engineering management

In 1916, Fayol (1949) wrote *General and Industrial Management* in which management was described as a process consisting of planning, organization, coordinating, directing and controlling. Lock (1993) named Fayol as the founding father of engineering management and modern management theory. In addition, Bennett (1996) cited the work of Fayol as the origin in the field of the management process forming the basis for much other work in this area.

Despite Fayol's pioneering work on management in the early 1900s, engineering management only emerged as a discipline in its own right in the latter part of the 20th century. As such, various interpretations of the term engineering management have emerged and, consequently, numerous definitions exist. Although engineering management has started to attain the status of a recognized discipline, research efforts in this field have been described as fragmented and uncoordinated (Lock 1993). Furthermore, Lock noted that in the current climate of rapid technological change and an intensively competitive global environment there is a demand for a renewed emphasis on effective engineering management and a re-evaluation of traditional attitudes and approaches. This point is echoed by Thamhain (1992), who recognized that today's engineering environment is more challenging than ever before due to increased technical complexity, and interdependency of technical tasks.

In addition to the need for a coordinated research effort in the field of engineering management, there is also a requirement to continue improving existing approaches and introduce new approaches. Duffy *et al.* (1993) indicated that improving the engineering design process will remain the focus of research until adequate solutions, which can be implemented in industry, can be found. On a similar theme, Andreasen *et al.* (1996) recognized that it is increasingly evident that significant improvements and efficiency gains can be made within engineering design since much time and effort is lost due to the lack of focus on both the application and management of design work.

There is a requirement for an improved approach to engineering management in order to cope with growing competitive pressure and increased complexity of the design development process and products. Competitive pressure is a perennial problem of engineering organizations compelling them to out-perform their contemporaries in order to be more attractive to existing and potential customers.

Engineering design has seen the advent of a range of management approaches, which have been implemented within industry. In order to identify the underlying concept of an improved approach to engineering management it is appropriate to briefly discuss a number of prominent existing approaches, specifically identifying the main focus of these approaches and their respective objectives.

2.1. Models of the engineering design process

The design process is viewed as a map for successful engineering work (Voland 1999). As such, models of the design process can be thought of as charting the course of action to be followed in order to carry out engineering design. Pahl and Beitz (1996) indicated that systematic procedures attempt to steer design effort from unconscious to conscious and more purposeful paths. It is perceived that a benefit of a systematic approach is that none of the stages of the design process will be inadvertently omitted. However, it is also viewed that such an approach may reduce the opportunity for creative design. Thus, design is a process requiring a systematic approach while simultaneously permitting the freedom for creativity (Hawkes and Abinett 1984, Shahidipour *et al.* 1999).

In order to improve the practice of engineering design, a variety of models of the design process have emerged over the past two decades. Models of the design process appear to have concentrated on the technical aspects of design rather than on the managerial aspects. Technical aspects are a key requirement of engineering design; however, managerial aspects also provide an opportunity for potential improvement. Indeed, Fayol (1949) recognized that management knowledge is the indispensable complement of technical knowledge. As such, it can be argued that models of the design process do not offer sufficient engineering management support to enable efficient process performance.

2.2. Concurrent engineering

Concurrent engineering is one of the most prominent contemporary engineering management approaches, which is reflected by the extensive research coverage it has received. One of the most often cited definitions of concurrent engineering is that offered by Winner *et al.* (1988), who defined it as 'a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developer from the outset, to consider all elements of the product life cycle from conception through disposal including quality, cost, schedule and user requirements'.

An aim of concurrent engineering is time reduction through performing activities in parallel. Indeed, Handfield (1994) indicated that the central point of concurrent engineering is the reduction of product development leadtime, which is achieved by collapsing activities so they are completed concurrently rather than sequentially. Ainscough and Yazdine (1999) viewed concurrent engineering as an initiative that can enable a company to reduce the time in which it designs, develops and introduces a product to the market by executing each phase of the product development process in parallel.

Concurrent engineering induces parallelism, which may contravene the relationships that exists between activities, with potential penalties attached such as exacerbating major re-work, resulting in additional financial costs and leadtime delays. Handfield (1994) statistically determined that while concurrent engineering can lead to shorter development times than sequential processes, the former will result in more defects than the latter. Thus, concurrent engineering can be considered to suffer from major drawbacks that could only be overcome by performing design work when and where appropriate. The concept of performing design work appropriately may include opportunities for concurrency.

2.3. Project management

A typical definition of project management is given as 'the planning, organisation, monitoring and control of all aspects of a project and the motivation of all involved to achieve project objectives safely within a defined time, cost and performance' (Smith 1995). From this definition and the numerous others offered, project management can be observed as comprising a number of main elements. These elements are regarded as planning, scheduling, control and monitoring. However, it is recognized that different authors place varying degrees of emphasis on each.

Project management can be thought of as a top-down approach (Cleetus *et al.* 1996) with the primary responsibility lying with a single person known as the project manager (Smith 1995, Lock 1996, Field and Keller 1998). The demands placed on this single point of management may not permit the effective performance of engineering design work. Thus, a bottom-up approach is required in order to allow management to permeate throughout a project team. In addition, the interactions between the various elements of project management are described at a level that can be considered inappropriate in terms of enabling its direct implementation and, thus, operation.

3. Coordination: an important and pervasive characteristic

Coordination has been observed as an important and pervasive characteristic within a number of interpretations of approaches to engineering management; for example, models of the engineering design process (Ray 1985, Cross 1994), concurrent engineering (Duffy *et al.* 1993, McCord and Eppinger 1993, Prasad 1996, Perrin 1997, Coates *et al.* 1999a), and project management (Oberlender 1993, Bailetti *et al.* 1994, Cleetus *et al.* 1996, Lock 1996, Bendeck *et al.* 1998). Indeed, coordination has been identified as being significant in several other approaches such as workflow management (Alonso *et al.* 1996, Yu 1996, Piccinelli 1998, Du and Shan 1999), design integration (Hansen 1995), and computer-supported cooperative work (Malone and Crowston 1994, Schal 1996). However, despite being widely cited, it can be seen that the understanding and appreciation of coordination varies considerably.

With regard to models of the engineering design process, Cross (1994) recognized that even with contrasting preferences in models, proponents of systematic procedures all agree that there are compelling reasons for improving traditional design procedures. One reason offered is that there is a need to coordinate a team of specialists such that their effort is made at the appropriate point in the process. Similarly, Ray (1985) described the technical management of engineering design as involving coordinating the work of a design team and assigning particular tasks to individuals or groups.

In the context of concurrent engineering, coordination has been described as the vehicle for its realization (Duffy *et al.* 1993), a main challenge (McCord and Eppinger 1993), and the principal requirement for its successful implementation (Coates *et al.* 1999a). In addition, Perrin (1997) stated that 'concurrent engineering is an organisational innovation which relies on new ways to divide and co-ordinate all the different activities implied by the design and development of a new product'. Prasad (1996) identified coordination as an element of cooperative teams within concurrent engineering organizations.

With regard to project management, Bailetti *et al.* (1994) viewed coordination as an important factor differentiating successful and unsuccessful projects, with performance in product development described as being linked to a higher degree of coordination. Oberlender (1993) defined project management as 'the art and science of co-ordinating people, equipment, materials, money, and schedules to complete a specified project on time and within approved cost', and, as such, the duty of the project manager was described as organizing a project team of people and coordinating their efforts in a common direction to bring a project to successful completion. It was also stated that coordination could be achieved through effective communication, specifically at regularly scheduled team meetings. On the theme of communication, Bendeck *et al.* (1998) implied that coordination could be achieved by providing a notification mechanism that keeps all team members up to date on the current project state. Lock (1996) indicated that project management involves planning, coordinating and controlling the complex and diverse activities of modern industrial projects, causing much of a project manager's time to be spent coordinating, which was described as steering and integrating the activities of some departments and relying on others for information and supporting services. Cleetus *et al.* (1996) stated that, previously, much emphasis in project management had been placed solely on management. It was implied that rather than control or management by one person, the objective should be coordination among people engaged in tasks. Coordination was said to be brought about by communication and responsible workers knowing about the completion of tasks on which they are dependent.

In summary, coordination has been recognized as an important and pervasive characteristic within a number of approaches to engineering management. However, the term coordination has been seen to have various meanings and, as such, there is a lack of a unified understanding. Thus, design coordination is proposed as being key to an improved approach to engineering management leading to performance improvements in the design development process. That is, design coordination does not just play a peripheral role in engineering management, but lies at the heart of an effective approach that is more comprehensive than any that currently exist. Indeed, with respect to engineering management, Duffy *et al.* (1999) stated that 'a more relevant, comprehensive, and appropriate approach is required for optimum performance', and, thus, suggested design coordination as such an approach. Similarly, Andreasen *et al.* (1996) identified that the effective coordination of the design process is the key to achieving optimal design performance.

Due to the varying perceptions of coordination it is recognized that there is a requirement for further research in this field with the aim of gaining a better understanding of its nature and potential as an approach to engineering management in its own right.

4. The nature of operational design coordination

In order to identify the key elements of operational design coordination, this section not only draws from literature related to engineering design, but also from organizational theory and distributed artificial intelligence. Literature has been included from these disciplines since they identify coordination as relevant and important, and a key research problem (Jennings 1993, Malone and Crowston 1994, Findler and Elder 1995, Nwana *et al.* 1996, Greenwood *et al.* 1997, Heck 1999).

4.1. Coherence

'Everyone has an intuitive idea of what co-ordination means, however it is difficult to explain what it is and why it is needed' (Cruz *et al.* 1996). Despite this reported difficulty, a number of authors have offered their respective view of coordination. For example, Fayol (1949) stated that 'to co-ordinate was to layout the timing and sequencing of activities, bind together, unify, and harmonise all activities and effort'. Further, Van de Ven *et al.* (1976) defined coordination as 'integrating or linking together different parts of an organisation to accomplish a collective set of tasks'. In addition, coordination has been regarded as involving 'the timely exchange of information and resources, the division and allocation of tasks, and the synchronisation of actions' (Kleinman 1990), and 'intelligent decision making agents sharing information and resources in order to solve a common set of tasks' (Findler and Elder 1995).

In the context of engineering design, coordination has been described as involving 'the effective utilisation of resources in order to carry out tasks for the right reasons, at the right time, to meet the right requirements and give the right results' (Duffy *et al.* 1999). Based on this description, Coates *et al.* (2000) reported 'co-ordination as the concept of the appropriate activities being performed, in a certain order, by a set of capable agents, in a fitting location, at a suitable time, in order to complete a set of tasks'. Also related to engineering design, Crabtree *et al.* (1997) identified a coordination challenge as 'how can each engineer's design tasks be managed so that it interacts and integrates well with the efforts and results of other engineers?', and intimated that a lack of coordination would lead to schedule delays, re-work, and cost increase. Wilson and Shi (1996) stated that 'engineering design problems are often solved by a group of individual participants with different expertise, loosely organised as a design team'. As such, it was recognized that design participant's activities must be coordinated in order to maintain coherence. Similarly, Durfee and Montgomery (1990) viewed a coordination technique as 'how a group of people organise themselves to work as a coherent team in order to accomplish some task'.

With regard to a distributed artificial intelligence setting, Chauhan (1997) indicated that coordination and coherence are related in that 'greater co-ordination results in a more coherent solution to the overall problem'. Bond and Gasser (1988) suggested that coherence involves how well the entire system behaves as a whole while solving a problem. On the theme of coherence, Nwana *et al.* (1996) viewed the prevention of chaos as a main reason for needing coordination and, thus, described coordination 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'. Chaos avoidance in multi-agent environments has been widely recognized as the requirement for coordination. For example, Jennings (1996) recognized that without coordination, the advantages of decentralized problem-solving disappear and a society of agents can rapidly become a collection of chaotic individuals. Similarly, Jamali *et al.* (1999) described several scenarios in which the lack of coordination in large agent ensembles resulted in chaotic behaviour.

4.2. Communication

Views of coordination have been reported as involving 'sharing information' (Findler and Elder 1995) and 'the timely exchange of information' (Kleinman 1990). Implicit within these perceptions is the aspect of communication, or interactions, between entities. Indeed, Cleetus *et al.* (1996) stated that 'co-ordination is brought about by communication'. Similarly, Carstensen (1996) stated that 'communication is the basic means of co-ordination'. de Jong (1997) elaborated by recognizing that most coordination mechanisms for multi-agent systems rely on the exchange of structured information.

Chauhan (1997) stated that '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'. Cruz *et al.* (1996) proffered that coordination problems arise in the organization of interactions of a group of entities that collaborate and cooperate to accomplish some task and to satisfy some goals. Jennings (1996) identified the dependencies between multiple agent actions as a main reason for the need to coordinate those actions. Bond and Gasser (1988) indicated that coordination is the interaction among a set of agents performing some collective action. As such, coordination has been viewed as the management of interactions between agents (Arbab 1998).

Coordination between team members was said to be maintained through meetings when problems arise and through consultation with the team leader (Hegazy *et al.* 1998). Fayol (1949) viewed conferencing of departmental heads as a means of informing a management of the running of a concern in order to clarify the cooperation to be expected between the various departments. The frequency of conferences was described as that which would ensure harmonizing activity (i.e. coordination). Hansen *et al.* (1997) conducted a study into coordination activities in the context of engineering design. Activity logs where used to measure the level of coordination (i.e. time used on meetings and planning as a percentage of the total time of the project). The findings of the study indicated that either a low or high level of coordination resulted in low project quality, whereas a medium level of coordination produced a high project quality.

Similar to the work of Hansen *et al.* (1997), Crabtree *et al.* (1997) conducted a study aimed at identifying coordination problems within collaborative design and assessing the proportion of an engineer's time attributed to performing coordination activities. A survey of engineering organizations showed that the time to complete a project increased by 20–30% as a result of coordination problems. Further, the survey revealed that in collaborative design, coordination activities occupied 69% of an engineer's time. These statistics corroborate with those indicated by Andreasen *et al.* (1996), who reported that engineers only spend approximately one-third of their time doing 'real design'. As such, it was stated that 'a considerable amount of time and effort is wasted by the lack of focus on the application and management of design effort' and 'the potential for improvement in better productive use of engineering design resource is substantial—providing we have the mechanisms to realise it'.

4.3. Task management

Coordination was reported as being viewed as 'steering and integrating activities' (Lock 1996), and 'the division and management of activities' (Perrin 1997). Furthermore, Fayol (1949) viewed an aspect of coordination as the laying out of the timing and sequencing of activities such they could be carried out in an orderly fashion. In agreement with these perceptions, Kleinman (1990) viewed 'the division and allocation of tasks' as an aspect of coordination, and Duffy *et al.* (1994) described the planning and control of activities as being central to design coordination. In addition, Decker and Lesser (1995) indicated that, in many application areas, individuals are responsible for deciding what order tasks should be done and when to do them.

A number of approaches to design management have been proposed with the emphasis placed on sequencing activities/tasks (Kusiak and Park 1990, Eppinger *et al.* 1994). However, these approaches are oriented toward concurrent engineering and, thus, focused on sequencing activities/tasks such that they could be performed/undertaken in parallel. Variations of Steward's (1981) design structure matrix are used in each of these approaches as a tool to re-arrange activities/tasks such that parallel groups could be identified. Furthermore, the nature of dependencies between activities/tasks is assessed, and relaxed if deemed to be weak. This feature of inducing concurrency departs from the view offered by Duffy *et al.* (1993), who emphasized that in order to optimize design, activities should not necessarily be carried out concurrently but, rather, coordinated (i.e. structured in a fashion as to achieve optimal performance).

An interdisciplinary study of coordination conducted by Malone and Crowston (1994) resulted in coordination being defined as 'the process of managing dependencies between activities'. This definition has been widely cited and influential in the areas of distributed artificial intelligence and organizational theory. For example, Lesser (1998) indicated that coordination of agent activities becomes necessary when there are interdependencies between them. Similarly, Cruz *et al.* (1996) described coordination problems as being primarily concerned with dependencies between the activities performed by the system entities.

The structuring or sequencing of activities/tasks, through the consideration of the dependencies between them, has been recognized as a key element of operational design coordination. However, when contemplating the structuring of activities/tasks, consideration must simultaneously be given to the resources available. Failure to consider resources may result in an optimized sequence of tasks with inadequate resources able to complete them in the desired manner. In reality, resources are scarce and, as such, need to be utilized appropriately with respect to the tasks they will be used to undertake and complete. Thus, the structuring of tasks is inextricably linked to the resources available, and, consequently, managing the assignment of tasks to resources (i.e. scheduling) is a key element that needs to be considered.

4.4. Schedule management

With regard to engineering design, Ray (1985) was reported as viewing coordination as 'assigning particular tasks to individuals or groups'. With regard to dedicated coordination research, the assignment of tasks to resources has also been recognized as an element to be considered. Malone (1987) viewed the assignment of tasks to processors as one of the fundamental components of coordination. Similarly, Findler and Elder (1995) considered assigning tasks to a group of geographically distributed agents as a coordination problem. Lesser (1998) indicated that coordination strategies enable groups of agents to solve problems effectively through decisions about which agents should perform which tasks and when, and whom should communicate the results.

In this paper, assigning tasks to resources is viewed as being synonymous with scheduling. In addition, planning is thought of as a pre-scheduling activity. Durfee (1993) indicated that planning has been viewed as the coordination problem by many researchers in the area of artificial intelligence. Goldmann (1996) differentiated between planning and scheduling by stating that 'planning is the division of tasks into sub-tasks' and 'scheduling is the assignment of resources and start and end times to tasks'. Similarly, Duffy *et al.* (1993) considered planning as the definition of the logical links between interrelated activities or tasks. Furthermore, in agreement with Goldmann, scheduling was viewed as specifying the resources and start–finish times of the activities, and as a means for the plan to be achieved. Duffy *et al.* also indicated that plans and schedules are not truly effective unless they are properly monitored and controlled. Likewise, Bendeck *et al.* (1998) recognized that coordination involves planning and scheduling, and monitoring during execution. In the context of engineering project management, monitoring has been described as the process during work of checking and verifying to compare actions and results with predictions and intentions, in order to demonstrate what changes are needed to overcome problems and achieve objectives (Wearne 1989). Thrampoulidis *et al.* (1997) also recognized that due to unexpected events, the realization of a planned time table is impossible. As such, it was asserted that there is a requirement to change, in real-time, the planned schedules of the resources. The determination of optimal changes in such cases was said to involve solving difficult combinatorial problems.

Due to the changeable nature of engineering design, potentially there is a requirement for plans and schedules to be changed, the need for which can be detected through monitoring. With respect to the need to change schedules (i.e. re-assign tasks to resources), dynamic scheduling is identified as a key element of operational design coordination, and, further, the management of this process.

Previously, task management was discussed leading to the recognition that in order to structure tasks appropriately, consideration must be given to the dependencies between them. Further, it was identified that the management of tasks must also involve the simultaneous consideration of resources. That is, the assignment of tasks to resources (i.e. scheduling) has been identified as a key element of operational design coordination. In addition, in order to ensure the appropriate assignment of tasks to resources throughout a changeable process or environment, dynamic scheduling has been identified as an extension of this element. Further, it has been identified that planning and schedule enactment must also be managed. Due to the recognized importance of the resources that tasks are assigned to, it is postulated that attention must be afforded to the management of resources, which includes monitoring.

4.5. Resource management

With regard to design coordination, the allocation of resources has been identified as an important task within design management (Andreasen *et al.* 1996). Duffy *et al.* (1993) stated that ‘the focus for supporting design co-ordination is directed at the effective utilisation and integration of resources in order to optimise design activity’. Design coordination has similarly been described as covering aspects of organization and management of resources, and control of the use of resources (MacCallum and Carter 1991).

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 (Smith 1980, Findler and Elder 1995). However, with regard to computing environments, Nguyen *et al.* (1996) recognized that the reduction in duration of many parallel applications is not proportional to the increase in the number of processors. On a similar theme, Coates *et al.* (1999b) presented an application of a design coordination methodology resulting in the observation that committing greater resources to a problem would not necessarily result in a proportional reduction of time to complete tasks. 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'.

Monitoring was previously discussed in the context of plans and schedules (Duffy *et al.* 1993, Thrampoulidis *et al.* 1997, Bendeck *et al.* 1998). The requirement for monitoring exists since 'the design of complex products involves the co-ordinated organisation of multi-disciplinary groups, activities and information which continually evolve and change during the design process' (Andreasen *et al.* 1996, Duffy 1998). Thus, monitoring is thought of as facilitating the detection of change such that, if appropriate, corrective action may be taken by performing re-scheduling.

Distributed computing systems need resource management capabilities that can allocate resources to applications, monitor and control the use of resources, and re-allocate resources due to anomalies (Davis and Sydir 1996). Thus, a need was identified for research to develop new techniques that will manage resources in a uniform and coordinated way within a dynamic environment. Kim and Lilja (1998) recognized that while resource scheduling has been the focus of much research over recent years, monitoring has been largely neglected. Musliner *et al.* (1991) also recognized the need to be able to detect and recover from discrepancies between the expected state and actual state during execution. Indeed, Ranganathan *et al.* (1996) indicated that deciding which resource to run particular applications can be based on monitoring variations in network characteristics. Nguyen *et al.* (1996) indicated that despite the inherent inaccuracies of runtime measurements, and the added overhead of more frequent re-allocations, schedulers using them can significantly out-perform those that do not. In addition, Garvey and Lesser (1994) considered monitoring as almost always providing a reduction in missed deadlines. A concern voiced by Wolski (1997) was that monitoring should be non-intrusive (i.e. should not compromise performance).

5. Conclusion

Effective engineering management is acknowledged as a means for contemporary engineering organizations to achieve and maintain a competitive advantage in an increasingly aggressive global market. The need to increase the competitiveness of organizations has resulted in the proliferation of a variety of approaches to engineering management. Furthermore, previously regarded as a ubiquitous characteristic of a number of approaches, coordination has been identified as important and pervasive; however, it was shown that currently there exists a broad and varied understanding. As such, the nature of operational design coordination has been discussed in sections 4.1–4.5, resulting in its key elements being identified as:

- *Coherence*—integrating, or linking together, resource effort and tasks within an organization in a harmonious manner to avoid chaos.
- *Communication*—interaction involving the exchange of structured and meaningful data, information and knowledge.
- *Task management*—the organization and control of tasks, and the dependencies between them, such that they can be undertaken and completed in a structured manner.
- *Schedule management*—managing the planning and dynamic assignment of tasks to resources, and the enactment of the resulting schedules, throughout a changeable design development process.

- *Resource management*—organizing and controlling resources to enable their continuous optimized utilization throughout a changeable design development process.

With regard to the key elements of *schedule management* and *resource management*, it has been recognized that engineering design is changeable due to the evolution of the multi-disciplinary groups, activities and information involved (Andreasen *et al.* 1996, Duffy 1998). Thus, a further key element of operational design coordination is identified as:

- *Real-time support*—how to manage and adapt to a changeable (i.e. dynamic and unpredictable) design development process.

Knowledge of these key elements provides the foundation for an approach to operational design coordination. The development of an approach that includes these key elements, by integrating the appropriate techniques, aims to provide a more comprehensive and improved approach to engineering management than currently exists. Furthermore, such an approach will involve communication between entities that enables the structured undertaking of inter-related tasks while continuously optimizing the utilization of resources, in accordance with dynamically derived schedules, in a coherent manner in real time within a changeable design development process.

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