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Integrating human factors and operational research in a multidisciplinary investigation of road maintenance

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There has been limited collaboration between researchers in human factors and operational research disciplines, particularly in relation to work in complex, distributed systems. This study aimed to investigate work at the interface between human factors and operational research in the case example of road resurfacing work. Descriptive material on the factors affecting performance in road maintenance work was collected with support from a range of human factors-based methods and was used to inform operational research analyses. Investigation of the case example from a different perspective, for the supply of asphalt from a distribution centre to multiple work locations, gave a broader picture of the complexity and challenges for the improvement of road maintenance processes. Factors affecting performance in the road maintenance context have been assessed for their potential for further investigation using an integrated human factors and operational research approach. Relative strengths of the disciplines and a rationale for ongoing, collaborative work are described.

Statement of Relevance: The paper provides evidence of the potential benefits of greater collaboration across human factors and operational research disciplines, using investigation of a case example in the complex, distributed system of road resurfacing.

Keywords: human factors; operational research; road maintenance; scheduling

1. Introduction

Researchers and practitioners in ergonomics/human factors seek to understand and optimise the performance of people in work systems. Operational researchers/management scientists have a similar motivation to understand work systems and there are useful examples of efforts to include aspects of human performance in mathematical models and simulations of systems or parts of systems (e.g. Baines *et al*. 2004, Mason *et al*. 2005). However, there are few examples of collaboration between the disciplines of human factors and operational research.

MacCarthy and Wilson (2001) have edited a book by researchers from human factors, production management, management science, operational research and psychology backgrounds, containing contributions on human factors in scheduling and planning. These focused on the performance of those involved in producing plans and schedules (e.g. how they make decisions or deal with complexity from the environment and context), but did not really consider the merits of collaboration between disciplines for the identification of work-related problems and the investigation and interpretation of factors affecting performance in the work system.

Lodree *et al*. (2009) presented a review of existing work which has attempted to integrate scheduling theory and human factors. This review concentrated largely on how aspects of human behaviour and performance can be accommodated in scheduling, although it was restricted to issues of job rotation, work–rest cycles and shift work, and related to scheduling situations at an individual level (e.g. an operator at a machine). A range of factors have been identified that need to be considered in scheduling, including skill learning and forgetting, individual differences, fatigue, stress, workload and motivation. Lodree *et al*. (2009) concluded that there are opportunities for collaboration on methods to determine task sequences that optimise performance and well-being and to develop a range of mathematical or modelling functions relating to anticipated variations in human performance.

Boudreau *et al*. (2003) considered the value of joint working for operations management and human resources management and referred to the need for

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operations management models that are 'richer and more realistic with regard to how they represent humans and their interactions with operating systems'. Boudreau *et al.* (2003) stressed the importance of application of the approach in the real world. This implies the need for progress in the investigation and modelling of complex systems, understanding more about the context of the work, learning about how humans behave in specific circumstances and developing an appreciation of the factors (individual, group or system related) that can affect performance.

The present paper reports on a feasibility study to explore the potential use of human factors methods in conjunction with operational research methods to understand more about factors affecting human performance in complex systems (i.e. comprising many parts and inter-connections, change and uncertainty). The approach used includes investigation of a case example; in this case, the optimisation of road maintenance work. This builds on previous work carried out at the University of Nottingham, examining safe and efficient access for engineering work on the UK rail network (Ryan *et al.* 2007, Schock *et al.* 2008, Wilson *et al.* 2008). Engineering work in the road domain is complex, involving contributions and interactions of staff in a range of disciplines, and is carried out in distributed locations, remote from suppliers of plant, materials and labour. The work is supported by various planning, scheduling and logistical arrangements to coordinate the different aspects of the work. There is a need for resourcefulness in the planning and completion of the work, to limit disruption to road users. A study in this type of complex context is therefore suitable for investigating the interface between the two research disciplines.

Human factors/ergonomics methods are particularly effective for the collection of information on tasks and activities during field observations and the collection of perceptions and experiences of those involved in different parts of the work through interviews, workshops or other variations of self-report approaches (e.g. Kirwan and Ainsworth 1992, Wilson and Corlett 2005). This information is vital for the understanding of the context of work activities, identifying the functions and key system components and determining the likely challenges for effective performance (e.g. efficient completion of the work) and well-being (e.g. safety of staff and road users). This provides a firm foundation for the development of solutions to any problems that are identified.

Operational research techniques such as mathematical modelling and critical path analysis can be used in resource constrained project scheduling to examine the sequences and timings of different activities under various requirements and constraints (e.g. maintaining the order in which some activities have to be conducted) (Brucker 2007). There are several examples of work reported in the literature on road work scheduling projects using optimisation methods (e.g. Mixed Integer Linear Programming (MILP) model (Ouyang and Madanat 2004, Williams 2006) or evolutionary algorithms (e.g. Glover and Kochenberger 2003, Hyari and El-Rayes 2006, Georgy 2008)) and computer simulations to test potential solutions for planning, scheduling or logistical problems (e.g. Nassar *et al.* 2003) and investigate the effects of uncertainties (Pidd 2004).

The aim of the current study was therefore to investigate work at the interface between human factors and operational research and, in particular, the feasibility of a combined human factors and operational research approach that could 'add value' in the understanding of activities, and identify the factors affecting optimal performance, in a complex environment. A programme of work by a multidisciplinary team, carried out by focusing on a case example of road resurfacing work, has been outlined. Outputs from this research included, first, development of understanding of the key components of road engineering and the factors affecting performance in the system. These findings have been used to produce preliminary conclusions on the types of human factors that can contribute to better operational research models in this domain and to start the debate on the requirements for inclusion in these models (i.e. what variables/factors should be considered, what type of information is needed, how it should be collected and how it should be presented). The work has also considered how operational research approaches and outputs can contribute to a better understanding and application of human factors in this type of domain. It is intended that the work in this collaboration should be a first step in integrating human factors and operational research approaches to complex systems.

2. Method

2.1. *Overview of the programme of work*

A case example of road maintenance has been used as a means of allowing researchers from human factors and operational research disciplines to work together to explore the interface between the disciplines in relation to a complex work environment. A study was commissioned originally by the Highways Agency (an executive agency of the Department for Transport, responsible for the operation of the motorways and other strategic roads in England), focusing on maintenance activities at specific worksites. The work has since been extended to allow a greater range of issues and problems that are relevant at the interface of the disciplines to be explored. Outputs from the case example have been used as a focus for this on-going work. The focus of the work has therefore been on what the case example can say about work at the interface between the disciplines. It is acknowledged at the outset that some simple models and assumptions have been used in this early stage of exploring the interface between the disciplines.

The research team was made up of experts from human factors and operational research disciplines, but also included a civil engineer, who acted as a domain expert and intermediary in discussions, posing questions that challenged some of the motivations and common assumptions within each of the disciplines. Early work in the collaboration involved discussions to understand the respective strengths of the disciplines, typical approaches and methods that were used, commonalities and differences in understanding and use of terminology and also requirements for the type and format of information needed. This provided useful introductory information on where each of the disciplines could assist or be assisted by the other.

2.2. *Details of the case example*

There were four phases of work within the case example and these were developed to achieve the following: to produce a sufficient understanding of the road domain and a basis for further in-depth study; to collect relevant contextual information on a selected part of the road maintenance domain, thereby providing relevant material for subsequent human factors and operational research analyses; to identify relevant variables (e.g. relating to aspects of human performance) in the context of the case example and examine the potential outputs from incorporating these in some common operational research models; to consider how robust the joint human factors and operational research approach might be when exploring broader or alternative perspectives of the problem, which are typical within complex systems.

The human factors and operational research contributions were directly or indirectly relevant within each of the phases of work and were therefore carried out interactively and in parallel. This was achieved through joint participation by human factors experts and an operational research expert (also accompanied by a civil engineer) in site visits, interviews and workshops. Findings and outputs from separate analyses were shared during the course of the study and key information was exchanged between the experts in an iterative process during the study to identify potential points of overlap in the areas of work.

2.2.1. *Phases of work in the case example*

The first phase was designed for the purpose of familiarisation with the road maintenance domain through a series of three site visits, interviews with staff from three different roles and review of relevant documents (e.g. guidance, regulations, organisational policies, work records). This enabled a narrowing of the focus in the second phase of the study for more detailed investigations of a job that was carried out over six weekend closures of the road at a specific worksite. Investigations in this second phase included the following:

- Collection of background information and provisional plans for the work through review of available planning documents and discussion of the weekly plans with the project manager.
- In-depth analysis of specific details of a selected part of the job in a workshop setting. This was carried out prior to the planned work, using a series of schematic diagrams (e.g. Figure 1) to help the workshop participants (project managers and site-based staff) to visualise workplace layouts (e.g. locations of vehicles, directions of paving, locations of staff) and to talk about expectations for completion of the work. The method for construction of these detailed plans of engineering scenarios, as used to date in trials in the rail industry, has been described in detail in Schock *et al*. (2010).
- Targeted site-based observations to look at particular areas of interest that were raised in the workshop and allow comparison of the actual activities with those that were planned.
- Collection of feedback from staff after the site work in a 'reflective workshop', approximately 2 weeks after the site visit, allowing opportunities for participants to review performance on the job as a whole and provide specific feedback on issues arising and lessons learned.

The third phase of the case example used outputs from the human factors based analyses in phase 2 to support an operational research-led approach to build two models: firstly, to carry out a critical path analysis to identify the optimal schedule for activities and determine the minimum duration of the road work; secondly, to investigate the costs associated with the optimal supply of asphalt material to one road maintenance worksite, determining the best order quantity of the supply of asphalt material over time, while minimising the relevant costs related to travel and waiting time for lorries. Input from the human factors expert was used in specifying relevant variables

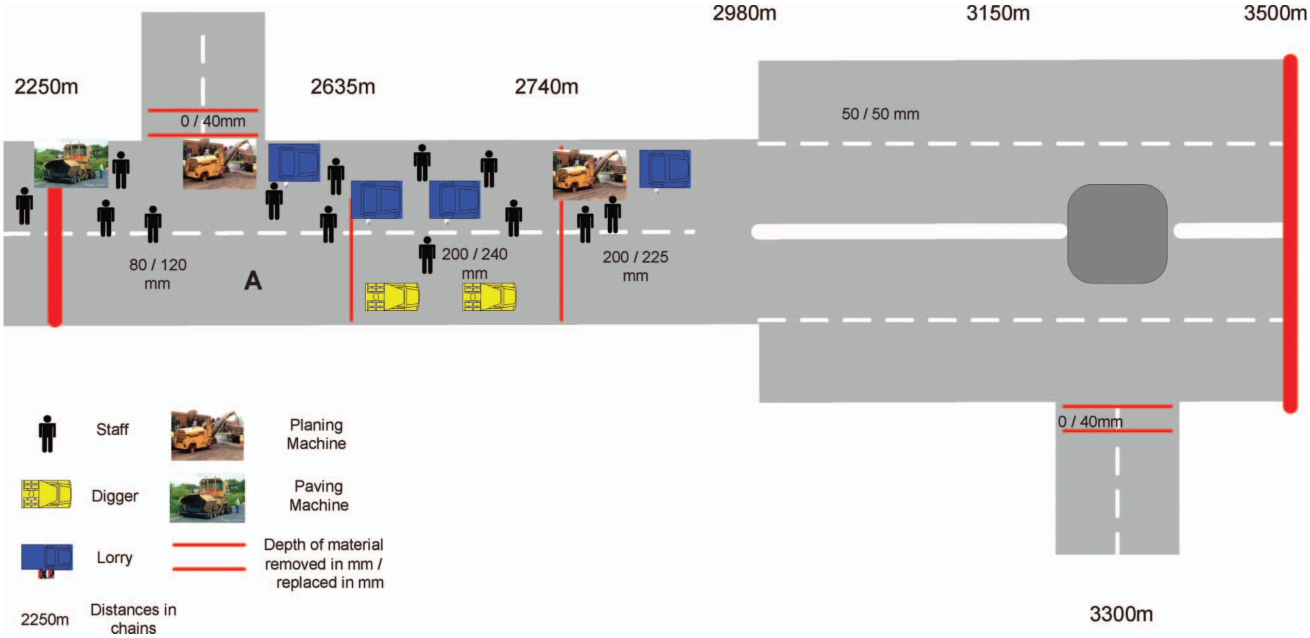

Figure 1. Schematic diagram of workplace layout, locations of workers and vehicles and details of proposed work, as used to prompt discussions at the workshops.

for inclusion in models and in supporting the interpretation of outputs from the models.

The fourth phase of the work broadened the scope of the problem, considering the implications of supply of different types of asphalt to multiple work locations, with activities at multiple manufacturing plants co-ordinated from a central distribution centre. An exploratory interview, led by the human factors expert, was carried out with two senior personnel at an asphalt manufacture and distribution centre, to understand the processes and the factors influencing the supply of asphalt materials to multiple work locations from a number of manufacturing sites. The interview collected details of key roles and responsibilities of staff at the distribution centre (e.g. distribution manager, manufacturing staff, drivers) and descriptive details of the process for planning and scheduling of arrangements for manufacture and supply of asphalt material in accordance with demands and changing conditions at worksites. Supporting organisational documents were reviewed. The review of literature was also expanded in this phase of the work, including studies that have investigated the specific issue of supply of asphalt material to worksites. Outputs from this review have been used in interpreting findings from the interview.

2.2.2. *Analyses of findings from the case example*

Comprehensive field notes were taken at site visits, including hand drawings of worksite layouts, which

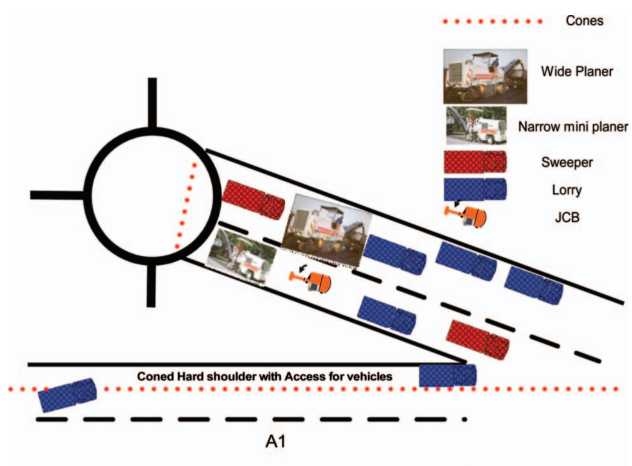

Figure 2. A schematic image of the operations and associated positions of vehicles at a given point in time during the 'planing' operation on a slip road on a carriageway, showing potential problems with access and coordination of vehicle movements.

were later reproduced for the purpose of presentation (e.g. Figure 2). Detailed handwritten notes were taken during the interviews, workshops and the review of relevant documentation. In the first two phases of the study, these notes were used by a human factors expert to produce a detailed description of the sequences of activities in road maintenance. A tabular record of the information was produced, structured by three key components of paving-related work (i.e. planning of the work; traffic management, including the design of diversion routes, setting up and removal of cones; the specific activities involved in the paving work). This description contained the following for each activity: which roles were involved; commentary on the circumstances affecting the completion of the activity; timings and dependencies. The breakdown and descriptions of different components of road maintenance were essential to experts in both disciplines.

The detailed descriptive record was used by the operational researcher in the construction of the models in phase 3 of the case example, for example, informing the operational researcher of important variations in durations of activities or constraints among activities (such as precedence constraints, where activity X must be completed before activity Y can be started). An activity-on-arc (AOA) network (Lawrence *et al*. 2002) was built using the breakdown and description of activities. The overall minimal duration of the jobs was calculated using a MILP model (Williams 2006) in the Microsoft Excel built-in Solver (Microsoft Corporation, Redmond, WA, USA), to identify the critical activities on the longest path in the AOA network, thereby modelling the linear relations (time constraints) between activities and calculating the optimal schedules (timings and sequences) for the list of activities. It was identified that one of the critical activities, which had the most significant effect upon the overall schedule, was the delivery of asphalt material to the site. This, together with other findings from the critical path analysis, was then examined in greater detail in human factors-led workshops. Feedback from domain experts at the workshops, supporting findings from the earlier analyses, prompted additional operational research analyses of the supply chain efficiency. An Economic Ordering Quantity (EOQ) model was built to determine the optimal order quantity and order time of supply of asphalt material, taking account of likely travel and waiting times for the lorries. Inventory management, balancing storing cost against the setting up of the production run, ensuring the delivery of materials on time, while minimising the relevant costs, is one of the earliest subjects studied in operational research (Harris 1913). Although the EOQ model is one of the most used models in inventory management (Axsäter 2006), the present authors are not aware of its use previously in research on road project scheduling. Most research in the literature focuses either on using MILP models for various scheduling problems (Voudouris and Consulting 1996, Kone *et al*. 2011) or EOQ models for inventory management (Guo *et al*. 2008, Ng *et al*. 2009). The present work has therefore considered the feasibility of integrating two basic MILP and EOQ models within a joint human factors and operational research approach, with a view to extending this to consider more problem-specific constraints in future work.

The descriptive detail of the road maintenance activities and broader context was also used for additional analysis by the human factors expert. Descriptive content from the record was categorised into a number of emerging themes, clarifying the range of factors affecting the performance at the worksite. Handwritten notes from the interview in phase 4 of the study, relating to the supply of asphalt to multiple locations, were subsequently reviewed and used to add to the range of factors affecting performance, using this broader view of the system. This list of factors affecting performance (introduced later in section 3.1.5) provided a useful record for the human factors and operational researchers of the range of components that would need to be considered in any subsequent models or other improvements to the work systems.

2.3. On-going examination of the interface between human factors and operational research disciplines, through examination of the identified factors affecting performance

A series of meetings of the researchers were conducted after the initial work on the case example to discuss the way forward on this collaborative work and to develop a more in-depth understanding about the respective disciplines and the potential areas of overlap in aims and approaches to solving problems. These meetings have enabled the researchers to become involved in more 'informed' discussions on terminology and methodology, which are used in the respective disciplines. As part of these meetings, the list of factors affecting performance in the case example (see sections 2.2.2 and 3.1.5) was reviewed to assess the progress and challenges ahead for modelling of relevant variables.

3. Results

3.1. Key findings from the case example, relevant to work at the interface between human factors and operational research

3.1.1. Descriptive analyses of paving work

Some examples of descriptive details of the activities and sequences of these activities are illustrated in the extract in Table 1, together with a summary of details of the context in which the paving work is carried out. The collection and interpretation of detailed information from workplace observations, or directly

Table 1. Extract from analysis of components in road engineering – activities in paving.

Activities	Details of the context in which activities take place
Specific paving related activities, including: Planing (where old material is removed to allow for replacement) –measurements, marking out and planing (wide planing, narrow planing); –sweeping, scrap clearance and visual examination; –measurements of depths of planing achieved, marking of requirements for paving	Variability in resources available, such as: lorries to remove planings, either from site or to storage prior to re-use on site; types (widths) and numbers of planers, sweepers and pavers (for subsequent activities). Variability in activities, dependent upon: road layout/configuration; specification for road materials (e.g. if recycling materials, whether facilities on site, or distance and journey to the storage or recycling location). Delay can be introduced by: limited availability of resources for subsequent paving; unexpected problems identified whilst planing out, resulting in need for additional examination by experienced staff.
Paving: tack/bond coat, –laying of paving surface, –heavy rolling of surface; –depth testing/other testing	Variability in activities, dependent upon: numbers of layers of paving and range of materials required (tack, bonding coat and different paving materials and mixes for different courses and locations); requirements for rolling different types of materials; space available (e.g. for work in multiple locations on sites, use of multiple pavers, access for lorries with material); weather conditions (e.g. need to consider the direction of paving in wet weather). Delay can be introduced by parts of the process (e.g. time for cooling of paving – ideally this will coincide with other periods of inactivity such as shift change), inconsistency of supply of asphalt material (e.g. as a result of plant breakdown or traffic congestion in delivery), effects of weather. Need for consideration of quality issues (e.g. where inconsistent supply of material and joints in paving, paving uphill or downhill, difficulties rolling to a good finish at night). Need for communication and coordination between team members (and wider team members) (e.g. knowledge of location of delivery vehicles). Site hazards (e.g. during rolling of hot material in the rain, producing steam which can affect visibility; overhead lines near to tipping lorries, steps in the planed out surface affecting vehicle movements; access for depth testing – leaning near to hot material)
Road marking – white-lining and road studs	Limited time available before opening of roads. Low cost work, but high visual impact. May be delayed because of longer than expected times for cooling and marking out. Detailing may be difficult in wet weather. Specialist contractors needed for some types of product. Contractors are required to work over large geographical areas, with lengthy travel time.

from participants in the process (e.g. using diagrams to prompt descriptive detail), are particular strengths of the human factors work. This type of detail on context can be imperative for understanding the range of factors that can influence performance and the potential interactions between these factors. The collection of this type of descriptive detail can be supported by operational research expertise, helping to specify the types of information that are needed (data types and format) in any subsequent operational research analyses. In this case example, the description and a first, qualitative analysis of sequences of activities provided a useful record of the context of the work and identified opportunities to revise the work processes and supporting arrangements (e.g. increasing the numbers of planing or paving machines). This preliminary analysis also indicated that there could be potential benefits from further investigations using operational research techniques, to provide a standardised representation of the sequences of activities and constraints, and examine potential variations in task sequences.

3.1.2. *Critical path analysis – modelling of task sequence, duration, order and constraints*

In scheduling research, some problem models can be assumed to be 'ready' and the models are usually simplified representations (Heard 1982, Ruiz *et al.* 2008). Operational researchers are trying to bridge the gap between theory and practice by modelling more realistic factors and constraints in scheduling. Currently, there is not a unified way to formally support the effective formulation of problems. This joint approach attempts to use expertise within both disciplines to get closer to this goal.

In this case example, work started from a real-world problem. The modelling was built based on the detailed description of activities from the interviews, workshops and site visits, providing details of sequences of activities and their timings, and also informing of the constraints for the operational research modelling. An extract from the AOA network is given in Figure 3. The figure illustrates relevant information, such as the activities and their durations, and the event times when all incoming activities are finished and outgoing activities can start. Thus, precedence constraints, where an activity must be complete before another can begin, can be easily identified. The activities that are on the critical path are also illustrated, determining the overall

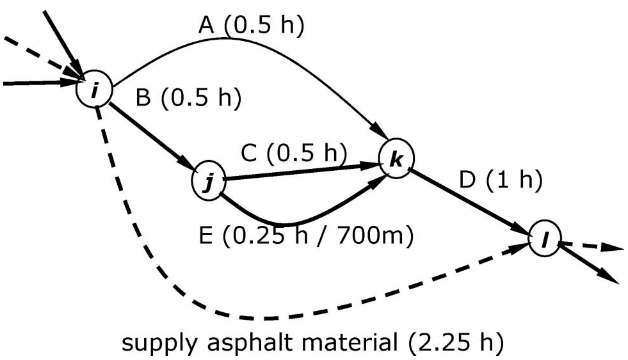

Figure 3. An extract from the activity-on-arc network for paving activities (partial). Arcs represent activities with values in parentheses as their durations; nodes represent event times, i.e. the time when all incoming activities are finished. Outgoing activities from a node cannot be started until all incoming arcs to the node are finished. Dashed arcs are critical activities, i.e. longest path between event times i and l.

project duration and indicating where efficiencies could be introduced to reduce the overall time needed for the job. As an example, use of the MILP model determined a minimum project duration, which was shorter than the actual completion time. This demonstrated the potential for efficiency savings of around 18%. However, this stage of the analysis does not include interpretation of the broad range of human factors that can impact on the practicalities of working to any changes in the schedule. As an example, a major constraint that was identified in the workshops and interviews was the need to eliminate the risk of extending work beyond the deadline for re-opening the road to traffic. Therefore, the decision of how much work to attempt in a given road closure period is made before the shift starts. This allows the latest weather forecasts to be consulted and asphalt supply issues to be considered. The extent of work is under constant review during the work period and operational research models cannot be realistic without acknowledging this type of factor. The joint working in this case example, taking account of the detailed information on the context of the work and the broad range of factors affecting performance which were obtained with the support of human factors expertise in the earlier field-based study, therefore enabled more realistic analysis of the potential for improving the schedule.

Figure 4 also identifies those activities that could become critical with delays (e.g. in the supply of asphalt materials) or with changes in the amount of work undertaken. The duration of activity E is dependent on the road length. For work of longer than 2.1 km, activities (arcs) B→E→D form the critical path between event times (nodes) *i* and *l* (i.e. the longest

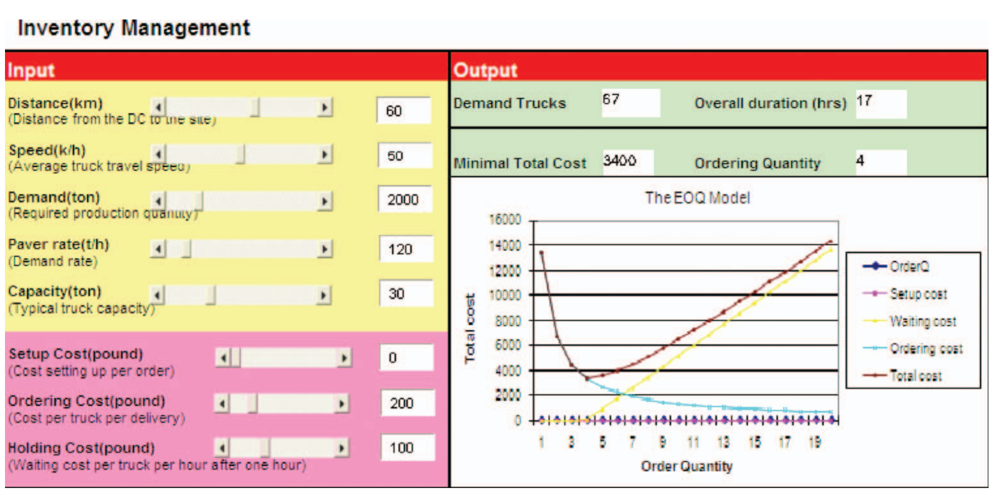

Figure 4. The Economic Ordering Quantity (EOQ) model for the inventory control of asphalt delivery. The left hand panel includes input of various factors and related costs. The right hand panel provides the output of the minimal cost, overall duration of the paving activity and the optimal quantity of ordering, taking into account the ordering cost and waiting cost of lorries on site.

duration to finish all activities between times *i* and *l*). However, the activity of 'supply asphalt material' is highly dependent on a number of uncertain factors, which were identified during the collection of detailed information in field-based work in site visits and interviews. This is an activity that could become critical (instead of B→E→D). The risk of delay is potentially one of the greatest weaknesses in the system of road maintenance, introduced largely through uncertainties in logistical arrangements for the removal and delivery of materials. Outputs from the descriptive parts of the work (the interviews and site visits) indicated that asphalt planings are usually removed from the site using a fleet of lorries and any break in the arrival of lorries can delay the process of planing. The supply of new, hot asphalt is by a fleet of insulated lorries, making a series of round trips between the asphalt production plant and the site of work, some miles away. Any uncertainty in the regularity of the supply of asphalt material has the potential to impact on the amount of work attempted in a given period of time and can introduce quality-related concerns where the supply of asphalt material is not continuous (McKeown *et al.* 2000). The arrival times of lorries for removal of material or supply at the site can be affected by a number of factors, including the numbers of lorries used, working time and driving hours regulations, the degree of traffic congestion and the distances between site and plant or storage location. Decisions related to the numbers of lorries for supply to the site can be influenced by factors such as cost and availability.

The operational research methods are particularly strong for analyses aimed at optimising performance through scheduling. In this case example, the formulation of the problem in the AOA network and MILP model for the critical path analysis was supported by human factors fieldwork and analyses, which identified key elements of planning, scheduling or logistics, and the constraints among activities. This part of the joint analysis indicated that further detailed examination of the delivery of asphalt material was needed to give insight to the effect of this critical activity on the overall optimal schedule. This part of the analysis would use additional operational research modelling techniques, but would need to incorporate components and sources of variability identified in the human factors fieldwork, thereby demonstrating the value of a joint approach to the study.

3.1.3. Analysis of the supply of asphalt to a single worksite

The supply of material to site was identified in site-based observations as a potential source of delay in the paving at the worksite. This activity was confirmed as one of the critical activities based on the critical path analysis using the MILP model. The EOQ model (Axsäter 2006) was built to analyse the cost for different ordering quantities over the time of the paving job, while balancing the waiting costs of lorries on site, as demonstrated in Figure 4. The factors included in the EOQ model have been informed by interpretation of earlier descriptive work in this study. The waiting cost of lorries on site was modelled using a check-up table in Excel (Microsoft Corporation), as waiting time in this context is a non-linear function of time (there is no cost within 1 h of waiting, with linear cost over time after that). Uncertainty in delivery time (based on the distance between the distribution centre and the site and speed) was modelled within the EOQ model by using a variable with a normal distribution of delivery time, to give an initial understanding of its effect on the cost and order quantities. Whilst the normal distribution has been used for the purpose of this preliminary model, investigations of uncertainties in operational research models represent challenging research issues to many researchers in the literature. Attempts to refine the understanding of this type of uncertainty, through further joint working between the disciplines, will be one future research direction.

Findings from the EOQ model (Figure 4) indicate that cost savings can be obtained by optimising the asphalt delivery process. Given the input of problem information (e.g. relating to distance, speed, demand, costs of waiting at worksite – see the input panel at the left of Figure 4), an optimal ordering quantity and minimum total cost can be calculated by the EOQ model. In the example shown in Figure 5, an optimal ordering quantity of four lorries has been determined, with a minimum total cost of 3400 units. This can be compared with a cost of around 4000 units if the ordering quantity is set at six lorries per order, indicating a potential saving in cost of around 600 units. Managers involved in the supply of asphalt in this case study have acknowledged the potential value in optimising the transportation process, reporting that transportation is their single biggest cost, doubling the cost of their operations. There is also support for these findings on transportation cost in the literature. Nassar *et al.* (2003) built a generic simulation model to assess paving operations in relation to partial road closures. They found that the number of trucks used in transportation had a significant effect on production rate and direct cost in asphalt paving operations. However, the number of available drivers is not necessarily under the control of the suppliers of the materials, because the drivers are usually independent owner–operators. More advanced modelling may be needed to take account of variables such as driver

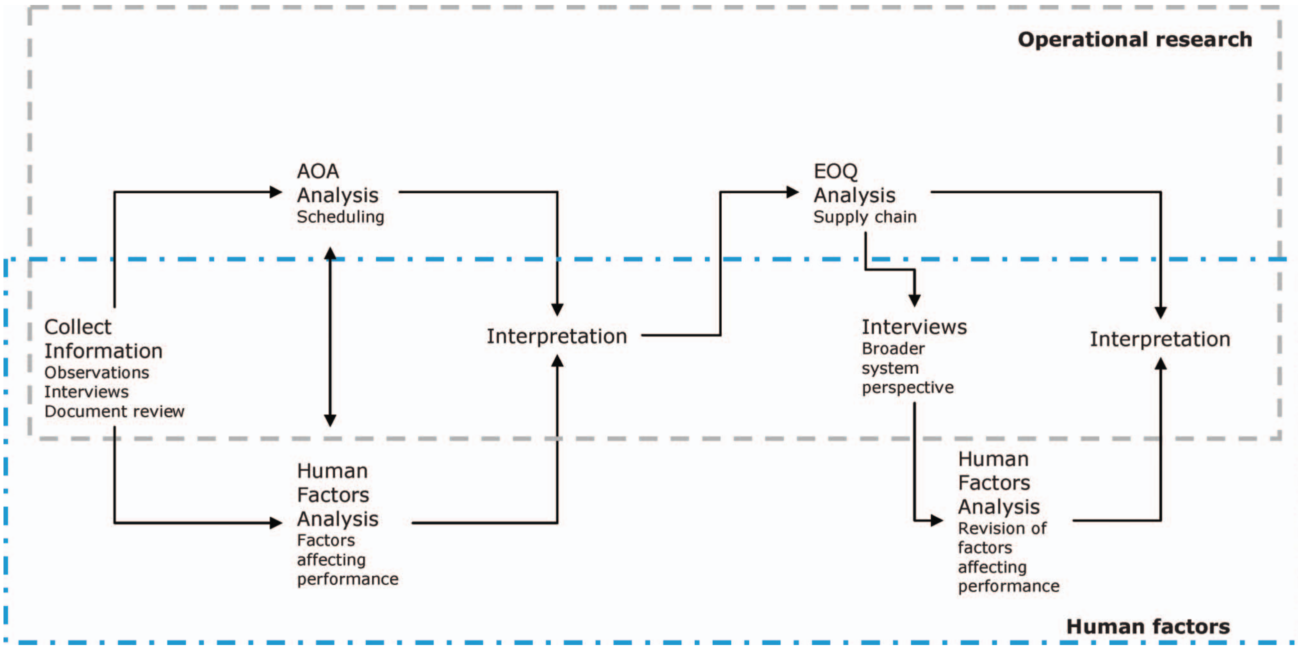

Figure 5. Overlap between the human factors and operational research work in the case example. AOA = activity-on-arc; EOQ = Economic Ordering Quantity.

availability and human factors methods may be needed to get a better understanding of factors that influence this, such as the motivations of drivers.

In future work, the EOQ model that has been developed will need to be extended to enable a sensitivity analysis on the cost of the delivery schedule and to enable flexibility in modelling of additional factors that have been identified in this joint study (see section 3.1.5). Extended mathematical or analytical models such as (Q,r) models may need to be studied to supplement the use of EOQ models for some factors. More advanced intelligent algorithms, such as evolutionary algorithms (Hyari and El-Rayes 2006, Georgy 2008), may be required, if more complex non-linear constraints need to be modelled in the MILP models for different real-world problems. This might assist understanding of factors such as decision making on efficient performance, taking into account a broad range of factors in the work system.

Operational research methods have been dominant in parts of the investigation, but these have been assisted by detailed information and interpretations provided by human factors experts. The in-depth analysis on the delivery of asphalt material using the EOQ model has added to the understanding of the effect of this critical activity on the overall optimal schedule, while minimising various costs in the complex system. In this particular study in the road maintenance environment, the human factors-led field-work has identified that uncertainty is evident in a number of different circumstances (e.g. affecting the timely supply of materials and disposal or recycling of road planings), impacting on the projected completion time for a job). These uncertainties for delivery time of lorries can be formulated in an extended EOQ model, to produce a research tool that would enable human factors experts to more quickly see the potential effects and potential interactions of potential changes within the system. Alternatively, the model could be developed to produce an efficient decision-making tool for the site managers in road projects.

3.1.4. *Investigation of the supply of asphalt to multiple sites*

Analyses up to this point reflect the focus of attention on the activities and the supply of materials to a single paving worksite. The interview with senior personnel at the asphalt manufacture and distribution centre provided an overview of the system from a different perspective, that is, in relation to the manufacture and distribution of asphalt to multiple worksite locations. In this part of the study, findings from the interview broadened the scope of the project, developing awareness of the complexities associated with the following: the coordination of the manufacture of a large range of specifications for asphalt materials across nine manufacturing plants; arrangements for the timely delivery from the asphalt plants to various worksites in the geographical region of the Midlands, using a pool of around 200 drivers. The interviewees outlined the processes involved in establishing a plan for manufacture and delivery of asphalt, using a capacity planning tool, but highlighted the need to respond to continuous change due to unplanned events and uncertainties. In contrast to the observations at a site-based level, the interviewees explained how there is likely to be very little tolerance in the system and the distribution managers are frequently required to manage customer expectations in the process of attempts to reschedule activities. This part of the work, which was led by the human factors expert, collected detailed contextual information from a different perspective of the system and revealed a broader range of factors that influence performance when taking account of the supply of asphalt to more than one worksite location.

This output from the case example has demonstrated the value of taking a broad system perspective. Earlier work focused on the system from the perspective of those working at the road worksite and revealed a number of important issues and factors affecting performance. From this rather narrow perspective, there may be some scope to review the efficiency of the scheduling (timing and sequencing) of activities under constraints, for paving at the worksite. This was supported by the preliminary operational research analyses in this study, which indicated the potential for a reduction in the overall completion time for the job. As an example, it could be possible to complete some activities more quickly and reduce the overall duration of the paving job (e.g. using multiple teams or wider planers in fewer 'rips' of the road surface).

In the latter part of the work, information was collected, which gave an appreciation of the system from the perspective of those in the distribution centre. This illustrated how consideration needs to be given to the implications of any changes on other parts of the system. This could include the increased demands and costs for equipment and lorries for removal of planings or the supply of asphalt materials. Part of the operational research analysis considered the costs for the optimal numbers of lorries for the supply of materials under different circumstances. Further refinements of this modelling could be useful for examining the uncertainty introduced by factors such as traffic congestion and variable distances between the asphalt plants and the site of work, with the aim of maximising outputs in different site conditions and circumstances. However, this is only a small part of the operational research problem relating to the manufacture and distribution of asphalt from the perspective of those at the distribution centre. Tolerance or slack in the system in parts of the work at the worksite seems to be necessary under current operating conditions to compensate for a lack of tolerance or slack at the distribution centre. There is clearly value, in future work, in focusing efforts on integrating human factors and operational research techniques, using a broad systems perspective.

The system-wide complexity seems to be recognised in some decisions that were taken at worksite level. There appeared to be no strong desire on the part of those consulted to attempt to achieve a shorter overall completion time by reducing timings for different components of the job. This apparent reluctance to shorten time for activities was perhaps through fear of losing the tolerances that they believed were necessary to deal with uncertainty arising in the process. Until the sources of, and, solutions to, this uncertainty are determined it will be difficult to find support to make process changes for greater efficiency. The joint human factors and operational research approach can work to develop understanding of this uncertainty.

3.1.5. Factors affecting performance in road maintenance

A primary objective of the current project has been to understand the sources of complexity in this example of activities in road maintenance and the range of factors that can affect performance. The understanding of the activities and the contexts in which they occur, including the use of two different perspectives of the distribution of materials, has been important in the identification of the factors affecting performance in the system. Through a series of descriptive and modelling-based analyses, a range of factors have been identified. These are presented in Table 2 (column 2). The list of factors is not likely to be exhaustive. However, in this feasibility study in this complex work domain, the factors have been drawn from a broad range of issues and topics that were uncovered in the observations, interviews, workshops and analyses (examples are given in column 3). These show good coverage across the classification of general factors (column 1), which is typical of general taxonomies in standard ergonomics texts. A number of these factors, and the issues from which they have been derived, are also consistent with findings from the literature. For example, Miller and Doree (2008) referred to the importance of communication between those at the plant and at site, and uncertainty arising from the lack of technology usage (e.g. for tracking delivery vehicles). Pohl (2003) listed a number of factors affecting timely delivery of materials, including the numbers of vehicles used, equipment breakdown, the space or configuration of the workplace (e.g. work at intersections), waiting times at site and the importance of customer–supplier relations and effective communication methods. Lee (2006) noted the effect of learning, with reduced task time as a project progressed over a number of shifts.

The list of factors is therefore an important output from this study and a useful guide for specific areas where further examination of the interface between human factors and operational research is necessary. The progress to date in modelling these factors is outlined in section 3.2.

3.2. *Key findings from other activities in the collaboration*

The researchers have continued, throughout a series of meetings, to broaden their understandings of what each of the respective disciplines have to offer in this type of investigation of a complex system. These discussions have become more meaningful as a result of the opportunities to consider the tangible outputs from the case example, prompting more in-depth questions of each other on terminology, methods, data requirements and the potential linkages with other, allied disciplines. As part of these discussions, factors that have been identified as affecting performance in the case example (Table 2) have been reviewed. A preliminary classification, given in Table 3, has been carried out to distinguish those factors affecting performance that have been modelled in the work so far, those that could be modelled using more sophisticated modelling techniques and those that would need more consideration (e.g. to determine the value of modelling).

This classification gives a preliminary indication of the progress to date and the scale of the work that is required in the modelling of parameters that have been found to be relevant in the road maintenance domain. The classification has been carried out by a small group of researchers and the present authors now intend to seek wider input from colleagues in their respective disciplines.

4. Discussion

What has actually been achieved in terms of research at the human factors/operational research interface?

First, a lot more is understood about the relative strengths of the different disciplines and the contributions that can be made through use of expertise in each discipline in the joint investigation of complex, real-world problems. This has taken account of important contextual details and different viewpoints of the system. These strengths and current limitations of the disciplines in the collection and analysis of data in this road maintenance scenario are summarised in Table 4. The respective contributions and overlap of the work of the disciplines is illustrated in Figure 5. Some of the research activities are common to both of the disciplines, although these can be conducted in different ways and collect different types of information. Where these activities can be carried out jointly, it has been found that they can be done in a way that assists other research activities and analyses (e.g. detailed analysis of context, mathematical modelling) within the respective disciplines.

This understanding of the disciplines is important in on-going attempts to develop collaboration. To date, there has been limited collaboration between the human factors and operational research disciplines (Lodree *et al.* 2009), in particular, in relation to the study of complex, distributed systems. The findings from this current study illustrate the potential benefits of integrating human factors and operational research approaches in future investigations and how the joint working of human factors and operational research disciplines adds value in the current case example of road maintenance. This study has identified the types of complexities and constraints in this type of system and the first steps have been taken in incorporating some of these in operational research models. The work gives insight into the inputs that are needed (e.g. for operational research models), examples of the types of information that can be collected and the types of analyses that can be conducted. The present work includes interpretation of the outputs from analyses, commenting on the potential usefulness of the findings within and between the disciplines.

Recognition of the importance of detail on the context of work activities has been an important part of the work. This recognition is common within the human factors discipline, but needs additional work to understand the potential impacts of some factors on performance (e.g. see work by Wilkin 2010, referring to the importance of the consideration of social factors in ergonomics studies). Inclusion of additional relevant parameters would enhance work in the operational research discipline and this might be achieved through the development of support tools or guidance. During this study, the researchers developed a good understanding of the different components of road maintenance work and descriptive details of the work contexts. This was an important first step in understanding the work processes, which also enabled the subsequent identification of factors affecting performance in the system. This detailed understanding of context was also necessary for identifying the sequences and timings of activities and the constraints for the operational research modelling. The methods used to capture information included general observations and consultation with staff (e.g. in interviews) and allowed opportunities for discussion and exchange of ideas between those involved in the

Table 2. Summary of factors affecting performance in road maintenance.

General Classification	Factors affecting performance	Examples of observations and findings from the current study
Individual	Knowledge, expertise	Key role of the Project Manager in coordinating activities, drawing on experience and recognition of need for interventions.
	Decision-making	Need for Project Manager to make frequent decisions on changes occurring at the site. Need for distribution managers to make real-time decisions, using their experience, on manufacture and supply of quantities of materials to multiple sites.
	Strategies	Project Planner and Project Manager have awareness of targets to be achieved at a fairly gross level of detail (e.g. remove and re-lay X tonne of material in a defined period of time, in the knowledge that they would be likely to experience some delays or challenges during that period). Consequently, a certain degree of tolerance is built into the work to allow for uncertainty, with the overriding aim of avoiding overruns at all costs.
	Flexibility	Need for flexible approaches from the Project Manager to deal with circumstances arising at the site, such as re-scheduling of the amount and type of work to be attempted because of the effects of weather, availability of materials, or identification of additional problems (e.g. after exposing surface course of road – requiring additional design and remedial works). Re-scheduling for the manufacture and delivery of asphalt in response to various site or environmental circumstances, with need for frequent adjustment to plans throughout the work.
	Learning	Potential for greater efficiency identified during the work (e.g. better arrangements identified for traffic management after learning from experiences of initial set-up, improved knowledge of routes and site access points for drivers on repeated journeys to site).
	Workload	Limited examination during the current study, although potentially high demands on the project manager and distribution manager may impact on decision making.
Teamwork/ cooperation	Support	Strong support for the project manager at site from planners/designers, though reports of limited input from supply chain in the planning of the work. Paving gang observed to work effectively as a team, with everyone knowing their role.
	Management of relationships	Importance of development of trust between asphalt supplier and customer. Need for negotiation, compromise and management of customer expectations when dealing with changes in demand for materials.
	Communication	Effective communication between site staff (e.g. verbal or through hand signals), between wider teams (e.g. drivers of delivery vehicles working effectively with paving team to load the paver). Variable provision for site/ delivery communications (see uncertainty below).
Equipment, vehicles, materials	Design and Availability	Work activities can be more efficient if specialist equipment is available (e.g. kerb planer for novel approaches to problem solving). Speed of paving can be influenced by numbers and types of plant/equipment. Supply or removal of materials can be dependent on numbers of drivers and vehicles available, and correct types of vehicles (e.g. insulated vehicles). Large variability in specifications for materials can introduce complexity in arrangements for manufacture and delivery of materials to multiple sites. Errors in delivery can occur (e.g. wrong material delivered to the location).
	Breakdown/ malfunction	Breakdown of plant (at site, manufacture, delivery vehicles) can delay paving.
Task/activities	Timings/task duration	Delivery time can be influenced by distance from plant to site, delay because of traffic congestion, waiting time at asphalt plant and site. Typical task durations can be established (e.g. planing, paving per linear metre), but can be influenced by factors such as road configuration, supply of material or vehicles, characteristics of materials (cooling time for laid asphalt can depend on the type of material and delivery temperature). Delays in starting work can be caused by higher than anticipated traffic flows.
	Uncertainty	Lack of knowledge of location of vehicles in some cases can impact on decision-making at site (e.g. whether to delay laying of paving) or at the distribution centre (e.g. whether to revise the delivery schedule). Global Positioning System tracking of asphalt supply is available for some organisations.
	Costs	Can be variable in some activities (e.g. for decisions on numbers of trucks for delivery and numbers of trips per truck, realistic costs would need to

(*continued*)

Table 2. (*Continued*).

General Classification	Factors affecting performance	Examples of observations and findings from the current study
		consider truck set-up – lubricating the truck bed, waiting times, and impacts on continuity of supply of materials at site).
	Product/process requirements	Activities need to be carried out in the correct sequence (precedence constraints – planing before paving), and integrated with other works (e.g. coordination with street lighting, drainage, structures). Asphalt production rates ideally need to be synchronised with paving rates at site, though there are logistical difficulties in achieving this.
Workplace	Space/ configuration of workplace	Layout/road configuration can impact on types of activities, paving rate, and site hazards (e.g. reduced width of road can inhibit use of multiple planers and pavers; plain line paving can be faster than paving at an intersection or roundabout; slope of the road can be important in some weather conditions; introduce greater risk from hazards such as proximity to vehicles and collisions).
Environmental/	Weather	Can cause changes in amounts and types of work attempted.
	Lighting	Work at night can have potential effects on quality of the surface or quality of kerbing.
Procedural	Standardisation	Structured design programmes and approved/planned diversions can simplify arrangements for planning.
	Planning	Continuous revision of plans for manufacture and distribution, from 3 months out to the day of the work, accounting for known sources of delay (e.g. planned roadworks, which can impact on delivery times). Continuous revision and response to changes during the course of the work.
Organisational	Tolerance/slack in system	Tolerance available at site, though plans are frequently overcautious in terms of work planned to limit the potential for overrun. Less likely to be tolerance available at the asphalt plant.
	Shift schedules	Need for adherence to working time requirements for drivers, site and manufacturing plant based staff. Potential to plan for process elements to maximise use of working time (e.g. planning for cooling of asphalt during shift changeover).
	Safety and environmental	High priority given to traffic management/separation of work areas from open roads. Site hazards include limitations in visibility when working near vehicles, especially in poor weather; proximity to overhead lines; hot materials; emissions/fumes. Opportunities for recycling, with potential to re-use some materials and reduce new material and transportation costs.
	Quality	Need for correct specification and supply of materials to site, consideration of temperature requirements for delivery of materials to site and during laying of materials, and attention to road surface characteristics on completion of work.
	Company structure/ Reorganisation	Changes in geographical boundaries can present potential impacts on local knowledge of staff (planning and scheduling of work and delivery of materials) and increase distances of travel from plants to worksites.
External factors	Actions/ Behaviours of road users	Lack of control over actions of drivers/road users. Traffic management procedures are designed to maximise separation of work areas from open routes. Road traffic can impact on delivery times for materials.
	Other agencies	Uncertainty re-authorisation for road schemes can delay planning activities.

design and completion of the paving work (e.g. including prompts using visual representations of workplace layouts in workshops). A range of potential stakeholders, from around 10 different roles, were involved in the work. The participants were open and candid and, with their wide experience, were a very useful resource in this study, enabling the collection of a large amount of information in a short period of time. Nevertheless, in developing this collaborative work and, to broaden understanding of the impact of a range of relevant factors, there will be value in taking opportunities to spend more time with a wider range of key staff, using more in-depth elicitation techniques to develop understanding of the relevant activities (e.g. Hignett and Wilson 2004).

On a connected issue, this work has also highlighted the impacts of looking at the system from different perspectives. Operational research usually concentrates on modelling part of a system. Human factors research and application advocates the use of a whole system approach, although there are clearly challenges in both describing and in attempting to model the complexities in the whole system. Nevertheless, the current case example illustrates the

Table 3. Preliminary analysis of potential decision support methods for modelling of factors affecting performance in the system.

Classification of factors for modelling	Factors	Decision support methods
Factors modelled so far	Task/activity duration	Project Evaluation and Review Technique (PERT) (AOA, critical path analysis, etc.), Mathematical programming (Integer programming, MILP)
	Uncertainty	EOQ*
	Costs	EOQ†
Factors that could be modelled with more sophisticated models or methods	Workload Shift schedules Product /process requirements Design and availability of vehicles, materials, equipment Space/configuration of workplace Planning	Simulations Advanced, search algorithms such as Evolutionary Algorithms for resource constrained project scheduling/planning
	Knowledge, expertise Decision-making Company structure, reorganisation	Knowledge-based systems
Factors needing more consideration	Strategies Quality Learning Support Management of relationships Communication Weather, lighting Tolerance/slack in the system Actions/behaviours of road users Safety and environmental	Integration of decision support methods with techniques in other disciplines

AOA = activity-on-arc; MILP = Mixed Integer Linear Programming; EOQ = Economic Ordering Quantity.
*In addition to the methods used so for this factor, the following methods could also be explored in future work – (Q, r) model, Markov decision processes, fuzzy theory.
†In addition to the methods used so for this factor, the following methods could also be explored in future work – Mathematical programming, PERT.

Table 4. Relative strengths and limitations of human factors and operational research methods.

	Relative strengths and limitations of human factors methods	Relative strengths and limitations of operational research methods
Collection of information	• In depth, contextual information from observations, interviews and review of documentation, including hazards, uncertainties, strategies used	• Quantitative identification of critical activities with regard to optimisation objectives and interactive assistance with the specification for, and collection of, information needed
Analysis	• Qualitative analysis, producing detailed understanding of the range of social, environmental, task and individual factors affecting performance. Limited quantification • Support for the identification of relevant parameters, constraints and uncertainties that can be modelled and examined in subsequent operational research analyses • Interpretation of the likely success of solutions, including interactions and the impacts of change in different parts of the system • Limited expertise/understanding of correct use of models for in-depth analysis	• Detailed modelling of constraints among problem elements • Automated optimisation of performance through mathematical programming and sensitivity analyses, including modelling of uncertainty • Quantitative investigation and testing of potential solutions to problems, which feed into human factors analysis for further detailed understanding of key factors affecting performance • Potential to oversimplify problems for modelling • Limited experience in categorising human performance

potential benefits of attempting to take a broad, rather than a narrow, system perspective in order to understand the range of potential constraints and the interaction of factors in this type of complex system.

As part of the development of understanding of the disciplines, it is recognised that researchers from each discipline cannot be an expert on all things. It is clear that each time that researchers meet to discuss the way forward on this collaborative work, they learn more about the potential value and depth of understanding within their respective disciplines and the areas of overlap in their aims and approaches to solving problems. Perhaps most importantly, whilst working on the types of problems that are typical of this complex, work-related context, the researchers recognise the need for expertise in terms of how to select from, and when to apply, the techniques from their respective disciplines. It is believed that this can only be achieved with more collaboration and more effective approaches to collaboration.

The work in this study has also been effective in highlighting the challenges for joint working. The work involved in bringing these disciplines together in this type of context is at a relatively early stage of development, but there will be benefit in continuing to work together and to define joint research needs and questions, in particular when considering how the resulting collaborative effort can be applied with consideration of broader perspectives of systems. In continuing to work together, there are a number of considerations. The first group relates to practical considerations, such as 'How can a vocabulary be developed that is common and understood between the disciplines?', 'How can the different research communities be brought together?' and 'Is it possible to define a strategy or route map for better collaboration?'. Additional questions relate to the particular contributions that each discipline can bring to the collaborative effort. In terms of human factors-led approaches, 'How can human factors research more effectively identify the problems that are likely to be solved by operational research, particularly in the context of the complexity within a broader system perspective?' and 'How can information that is extracted from the site-based observations and interviews with staff be described and represented in such a way as to exert better influence and be better represented in mathematical models?'. In terms of operational research-led approaches, 'How can the operational research discipline influence the development of better, more efficient human factors methods?', 'What human factors issues have greatest impacts on operational processes, as illustrated through operational research analyses?' and 'How can human factors expertise be best used in refining models, interpreting quantitative outputs and supporting the validation of outputs from these models?' (e.g. using input from relevant stakeholders).

A second achievement of this research at the interface of the human factors and operational research is that a wide range of factors that can affect performance have been identified, which are of interest to researchers in both disciplines. The factors identified in Table 2 (column 2) give an indication of the types of factors that can contribute to better operational research models, not only for this type of road context, but also with wider application to other contexts. Boudreau *et al.* (2003) and Lodree *et al.* (2009) referred to the importance of considering factors such as workload, learning, stress, motivation and cognition in operational research models. A number of these have been found to be important determinants of performance in the current study. Factors such as motivation and stress, whilst not identified explicitly in the current study, are likely to impact on performance and could be investigated using other methods of empirical study. Additional factors such as these could usefully be added to a list of potential factors affecting performance.

This feasibility study has helped to contribute to understanding, at a conceptual level, which factors may be important. Further work is now needed to determine how the identified factors are considered currently within the respective disciplines and how they can be given greater consideration through future joint working. For example, from a human factors perspective, different dimensions of mental workload can be measured using a range of tools, for example, focusing on demands from activities or the time available, and these can be investigated using a range of methods (e.g. self-reported ratings; Pickup *et al.* 2005). The challenge for the current, collaborative work will be to collect relevant information in a format that is suitable for expression (e.g. as a mathematical function) and apply this in the correct type of operational research model. This will be achieved through close working between the disciplines, drawing on the expertise of the respective researchers in the application of the methods.

It is unlikely that everything can be modelled satisfactorily. The preliminary classification in Table 3 has taken the first steps towards defining the challenges that lie ahead for the development of operational research/decision support methods to be used to understand more about the range of factors affecting performance. It is important to recognise that this is the early stages of this work and there are theoretical and practical challenges going forwards, in particular in attempting to understand these factors and to consider modelling of more variables. The research so far has been intended to be illustrative of an approach to integrating the disciplines and work is now needed with a wider group of human factors and operational research experts to prioritise the factors that will have the greatest impacts in terms of performance and the highest potential for developing understanding through operational research modelling.

5. Conclusions

This feasibility study successfully demonstrated the potential to apply human factors and operational research techniques together, to develop a better understanding of the complex activities and the implications of different contexts and perspectives of the case example in road maintenance. A range of factors affecting performance in the system have been identified. Human factors methods are particularly useful for collecting and interpreting information in field studies from observations at worksites and directly from participants, identifying potential interactions between factors and specifying components for examination in subsequent operational research analyses. Operational research methods are strong in the modelling of critical activities and constraints among elements of a problem, producing quantitative outputs that can give tangible feedback on likely performance within a system. Progress has been made in modelling some of the factors affecting performance in the system. Using wider representation from human factors and operational research experts, work is now needed to examine the potential for modelling some of the more complex factors as parameters within operational research approaches, to enable solutions to be identified as part of a multidisciplinary approach.

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References

Axsäter, S., 2006. *Inventory control*. International Series in Operations Research and Management Sciencez, second edition. Berlin: Springer.

Baines, T., *et al*., 2004. Humans: the missing link in manufacturing simulation? *Simulation Modeling. Practice and Theory*, 12, 515–526.

Boudreau, J., *et al*., 2003. On the interface between operations and human resources management. *Manufacturing and Service Operations Management*, 5 (3), 179–202.

Brucker, P., 2007. *Scheduling algorithms*. Berlin: Springer.

Georgy, M.E., 2008. Evolutionary resource scheduler for linear projects. *Automation in Construction*, 17, 573–583.

Glover, F. and Kochenberger, G., eds., 2003. *Handbook of metaheuristics*. International Series in Operations Research & Management Science, vol. 57. Berlin: Springer.

Guo, Q., *et al*., 2008. A joint inventory model for an open-loop reverse supply chain. *International Journal of Production Economics*, 116 (1), 28–42.

Harris, F.W., 1913. How many parts to make at once. *The Magazine of Management*, 10 (2), 135–136.

Heard, E.L., 1982. Bridging the gap between theory and practice in production and inventory control. *Engineering Costs and Production Economics*, 6, 119–129.

Hignett, S. and Wilson, J.R., 2004. The role for qualitative methodology in ergonomics: a case study to explore theoretical issues. *Theoretical Issues in Ergonomics Science*, 5, 473–493.

Hyari, K. and El-Rayes, K., 2006. Optimal planning and scheduling for repetitive construction projects. *Journal of Management in Engineering*, 22, 11–19.

Kirwan, B. and Ainsworth, L.K., 1992. *A guide to task analysis*. London, UK: Taylor and Francis.

Kone, O., *et al*., 2011. Event-based MILP models for resource-constrained project scheduling problems. *Computers & Operations Research*, 38 (1), 3–13.

Lawrence, J.A., Pasternack, B. and Pasternack, B.A., 2002. *Applied management science: Modeling, spreadsheet analysis, and communication for decision making*, second edition. Hoboken, USA: John Wiley and Sons.

Lee, E.B., 2006. Accelerating urban highway rehabilitation with construction analysis software. *Federal Highway Administration FOCUS Magazine*, FHWA-HRT-06–026.

Lodree, E.J., Geiger, C.D. and Jiang, X., 2009. Taxonomy for integrating scheduling theory and human factors: review and research opportunities. *International Journal of Industrial Ergonomics*, 39, 39–51.

MacCarthy, B. and Wilson, J.R., eds., 2001. *Human performance in planning and scheduling*. London: Taylor and Francis.

McKeown, A., *et al*., 2000. Improving the longitudinal profile and evenness of asphalt pavements. *Pavement surface characteristics of roads and airfields, 4th International Symposium*, Nantes, PIARC 2000.

Mason, S., *et al*., 2005. Improving the design process for factories: modeling human performance variation. *Journal of Management Systems*, 24, 47–54.

Miller, S. and Doree, A., 2008. Improving logistics in the asphalt paving process – what we learn from planners logic? *24th ARCOM conference*, 1–3 September, Cardiff, UK. Association of Researchers in Construction Management, 381–390.

Nassar, K., Tahbet, W., and Beliveau, Y., 2003. Simulation of asphalt paving operation under lane closure conditions. *Automation in Construction*, 12, 527–541.

Ng, C.T., *et al*., 2009. The EOQ problem with decidable warehouse capacity: analysis, solution approaches and applications. *Discrete Applied Mathematics*, 157 (8), 1806–1824.

Ouyang, Y. and Madanat, S., 2004. Optimal scheduling of rehabilitation activities for multiple pavement facilities: exact and approximate solutions. *Transportation Research Part A*, 38, 347–365.
Pickup, L., *et al*., 2005. The Integrated Workload Scale (IWS): a new self-report tool to assess railway signaller workload. *Applied Ergonomics*, 36, 681–693.
Pidd, M., 2004. *Computer simulation in management science*. Chichester, West Sussex, UK: John Wiley and Sons.
Pohl, R., 2003. *Achieving better efficiency in the transport of hot mix asphalt to site from a fixed plant in Gauteng*. University of Pretoria: Department of Construction Economics.
Ruiz, R., Serifoglu, F.S., and Urlings, T., 2008. Modeling realistic hybrid flexible flowshop scheduling problems. *Computers & Operations Research*, 35 (4), 1151–1175.
Ryan, B., *et al*., 2007. Human factors in the management of engineering possessions: the roles of the engineering supervisor and PICOP. *People and rail systems: Human factors at the heart of the railway*. Aldershot, UK: Ashgate, 331–342.
Schock, A., *et al*., 2008. Use of visual scenarios to understand and improve engineering work on the UK railway. *Contemporary ergonomics*. London, UK: Taylor and Francis, 564–569.
Schock, A., *et al*., 2010. Developing scenario analysis techniques to understand functions and risks in the planning of rail engineering. *Production Planning and Control*, 21, 386–398.
Voudouris, V.T. and Consulting, A., 1996. Mathematical programming techniques to debottleneck the supply chain of fine chemical industries. *Computers & Chemical Engineering*, 20, S1269–S1274.
Wilkin, P., 2010. The ideology of ergonomics. *Theoretical Issues in Ergonomics Science*, 11, 230–244.
Williams, H.P., 2006. *Model building in mathematical programming*, fourth edition. Chichester, Sussex, UK: John Wiley & Sons.
Wilson, J.R. and Corlett., E.N. eds., 2005. *Evaluation of human work*, third edition. London: Taylor and Francis.
Wilson, J.R., *et al*., 2008. Understanding risk in rail engineering work systems. *Ergonomics*, 52 (7), 774–790.