27th Australasian Transport Research Forum, Adelaide, 29 September – 1 October 2004

Paper title: **Modelling issues on the railway resource management process using multi-agent system**

Author(s) name(s): Chi-Wai Tsang and Tin-Kin Ho

Organisation(s): Department of Electrical Engineering, The Hong Kong Polytechnic University

Contact details:

Postal address: Hung Hom, Kowloon, Hong Kong

Telephone: (852) 2766 6143, (852) 2766 6146
Facsimile: (852) 2330 1544
email: tcwden.ee@polyu.edu.hk, eetkho@polyu.edu.hk

Abstract (200 words):
The recent restructuring process in railways aims to improve the resource utilisation and quality of service. Such process involves separating the railway organisation into a number of stakeholders who are commercially driven to compete for rail resources (e.g. tracks and rolling-stocks) and consumers (passengers and freights). Computer simulation certainly helps evaluate strategies on resource management and optimise business objective. An efficient simulation model is the first step. This paper identifies the key modelling issues of the reformed railways by reviewing the impacts of restructuring on business management, engineering operations and regulatory issues. It has been found that the essential modelling elements are distributive entities, resource negotiation process and rationality. While most conventional models are unable to capture all these characteristics, the advances of modelling approach of multi-agent systems (MAS) can be adopted to represent the stakeholders by software agents which are autonomous and capable of rational behaviour and communicative acts. MAS for the restructured railways will be proposed for modelling and the potential advantages of MAS applications in railway engineering will be highlighted.

Introduction

Many infrastructure and necessity systems such as electricity and telecommunication in Europe and the Northern America used to be operated as constitutional monopolies, if not state-owned. However, they have now been disintegrated into a group of smaller companies managed by different stakeholders. Railways are no exceptions. Since the early 1980s, there have been reforms in the shape of restructuring of the national railways in different parts of the world. Continuous refinements are still conducted to allow better utilisation of railway resources and quality of service.

There has been a growing interest for the industry to understand the impacts of these reforms on the operation efficiency and constraints. A number of post-evaluations have been conducted by analysing the performance of the stakeholders on their profits (Crompton and Jupe 2003), quality of train service (Shaw 2001) and engineering operations (Watson 2001). Results from these studies are valuable for future improvement in the system, followed by a new cycle of post-evaluations. However, direct implementation of these changes is often costly and the consequences take a long period of time (e.g. years) to surface.

With the advance of fast computing technologies, computer simulation is a cost-effective means to evaluate a hypothetical change in a system prior to actual implementation. For example, simulation suites have been developed to study a variety of traffic control strategies according to sophisticated models of train dynamics, traction and power systems (Goodman, Siu and Ho 1998, Ho and Yeung 2001). Unfortunately, under the restructured railway environment, it is by no means easy to model the complex behaviour of the stakeholders and the interactions between them.

Multi-agent system (MAS) is a recently developed modelling technique which may be useful in assisting the railway industry to conduct simulations on the restructured railway system. In MAS, a real-world entity is modelled as a software agent that is autonomous, reactive to changes, able to initiate proactive actions and social communicative acts. It has been applied in the areas of supply-chain management processes (García-Flores, Wang and Goltz 2000, Jennings, Norman, Faratin, O'Brien and Odgers 2000, Jennings, Faratin, Norman, O'Brien, Odgers and Alty 2000) and e-commerce activities (Au, Ngai and Parameswaran 2003, Liu and You 2003), in which the objectives and behaviour of the buyers and sellers are captured by software agents. It is therefore beneficial to investigate the suitability or feasibility of applying agent modelling in railways and the extent to which it might help in developing better resource management strategies.

This paper sets out to examine the benefits of using MAS to model the resource management process in railways. Section 2 first describes the business environment after the railway reforms. Then the problems emerge from the restructuring process are identified in section 3. Section 4 describes the realisation of a MAS for railway resource management under the restructured scheme and the feasible studies expected from the model. To support the feasibiltiy of adopting the proposed model, a breif description on a related application is also included.

Types of restructuring

Table 1 summarises the years when five countries began to restructure their national railways.

Table 1 Major railways restructuring

Year	Country	Principle Legislation
1980	USA	Staggers Act
1987	Japan	Railway Enterprise Law
1993	China	Railway Act 1992
1994	UK	Railways Act 1993
1995	Australia	National Competition Policy

Although not shown in the table, countries such as Canada, Germany, France and Switzerland have also introduced reformative acts on their railways. Despite the differences in the details of the reforms, certain similarities can still be identified. In particular, the UK reformation adopted both vertical and horizontal separations, which are the popular approaches in railway restructuring. As a consequence, the following mainly focuses on the restructuring process in UK and only highlights the current organisation structures in the remaining countries.

Restructuring in UK

The UK restructuring process is more commonly known as privatisation since the process is accompanied with a change of ownership from the government body to the private sector. Prior to the reform, the national system was operated by the British Rail (BR). Under the management of BR, passenger and freight train operations were sub-divided into sectors, and each piece of infrastructure in a region was managed by the 'prime user' amongst one of these sectors (European Conference of Ministers of Transport [ECMT] 2001).

The need for privatisation was derived from the continuous loss of market share to road traffic. In 1952, the ratio of freight moved by rail and road was approximately 1:1 while this figure dropped dramatically to 1:9 prior to the privatisation in 1994 (Department of the Environment, Transport and Region [DETR] 1998). The main reason was generally considered to be over-regulation, which had resulted in poor adaptation to market expectation through the rigid pricing structure and poor quality of service.

Owing to the success of privatisations in other national businesses such as electricity, gas and telecommunications (Crompton and Jupe 2003), the British government decided to extend the process to BR so as to allow competition in the railway market. Competition was expected to be an effective means to reduce expenditure and increase revenue (Jensen 1998). The stakeholders now experience pressure from the railway market in which the customers are allowed to choose amongst the service providers. As a result, the stakeholders will attempt to eliminate any unnecessary expenses to improve their operating efficiencies. To maintain their sales of service, they are also pressed to improve the quality of service.

Competition in UK was introduced by vertical and horizontal separations. Vertical separation refers to the allocation of responsibilities to different stakeholders along the supply chain. For example, the infrastructure provision is separated from train service provision. Within each category of stakeholders (e.g. train service provision), horizontal separation sub-divides the operations into different types (e.g. freight, passenger, intercity, and regional services) and

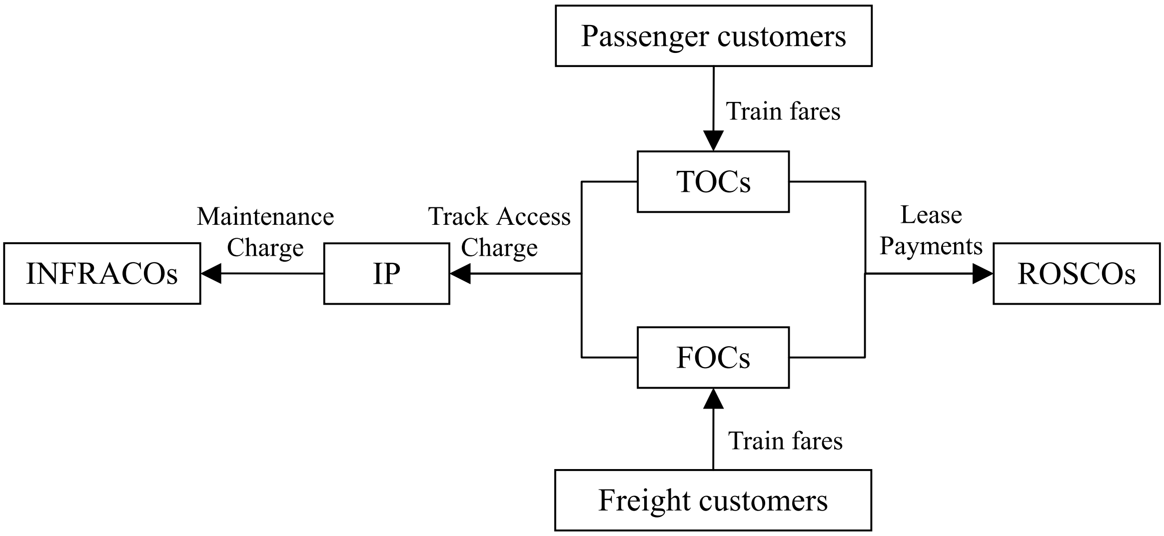

Figure 1 Structure of the British rail systems after privatisation

distributes the ownerships amongst different stakeholders.

Vertical separation in BR resulted in infrastructure provision, infrastructure maintenance, train service provision and rolling-stock provision. With the exception of infrastructure provision, horizontal separation was applied to all categories. The current railway structure in UK consists of one infrastructure provider (IP), 25 passengers train operating companies (TOCs), 2 freight operating companies (FOCs), 13 infrastructure maintenance and renewal companies (INFRACOs) and 3 rolling-stock leasing companies (ROSCOs) (Crompton and Jupe 2003). The business relationships between these companies are depicted in Figure 1.

Restructuring in other countries

In Australia, the restructuring approaches were different in different states. Southern Australia, Tasmania, and Western Australia transferred their ownerships to private companies while maintaining their vertically integrated structures. On the other hand, Victoria and New South Wales adopted both vertical and horizontal separations similar to the UK approach, except that ownerships still remained with the state governments. Only Queensland continued to operate as a vertically integrated state-owned corporation. An infrastructure provider called Australian Rail Track Corporation (ARTC) was formed to provide track access across the continent (Department of Transport and Regional Services [DOTARS] 2002).

The reformations in USA and Japan resulted in vertically integrated railways distributed across the geographical terrain. In other words, train service operation and infrastructure provision are still managed by the same corporations. However, there were horizontal separations with respect to the passenger and freight services. For example, freight operators in Japan are required to obtain track access rights from the operators of passenger services (ECMT 2001).

Although railways in China maintain both vertical and horizontal integrations as the Ministry of Railways (MOR), the management responsibilities for the railways have been allocated to the regional railway administrations through the decentralisation process (Xue, Schmid and

Smith 2002). Charges for freight movement are no longer strictly regulated but can be negotiated with MOR within a set upper bound set (Xie, Chen and Nash 2002).

Problems associated with restructuring

Despite the intention to resolve the inefficiencies in the monopoly system, the restructuring process generated new problems with respect to management operations, engineering operations and regulations. Moreover, if the activities are to be modelled and implemented in computer simulations, additional challenges inevitably arise.

Management issues

A number of stakeholders are created in the restructuring process. Through vertical separation, none of them possess all the necessary resources to provide train services. As a result, stakeholders need to interact with, and request resources from other parties. The interaction takes the form of negotiation. When resource is required, the stakeholder (initiator) will begin a conversation with the relevant stakeholder(s) (resource managers), querying about the charge of utilising the resource.

The resource managers may then reply according to the resource availability and cost. If the price exceeds the acceptable limit of the initiator, a counter-offer is then proposed. In fact, owing to the pressure of competition, all stakeholders are likely to minimise their operating cost individually, and efforts are needed to resolve disputes over the pricing of resources.

In other words, the resource management problem is now distributed amongst the stakeholders, each of which attempts to conduct local optimisation. Prior to the reforms, resources are allocated centrally by optimising the benefits of the entire corporation. However, in a restructured railway, the optimisation process is now distributed amongst the self-interested stakeholders. A solution that is optimal to one stakeholder may not be necessarily optimal to the others. Negotiation is a process through which the stakeholders settle at a feasible arrangement. To allow efficient allocation of resources, it is therefore important to evaluate the negotiation strategies for the parties involved.

Engineering issues

During the negotiation on resource utilisation charge, it is also necessary to consider the engineering constraints in order to avoid incompatibility and in the worst cases, collisions or derailments. For examples, between the negotiation of an infrastructure provider and a service operator, attributes such as axle load and line speeds have to be checked before an agreement is made (ARTC 2002, Strategic Rail Authority [SRA] 2003). When railways were operated as corporations, engineering incompatibilities on rolling stocks, speed limits, traction equipment, and signalling systems were easily detected because of the complete knowledge of their inventory. On the other hand, in the reformed environment, an infrastructure provider has to form contractual agreements with the service providers to ensure these engineering requirements are satisfied. It is vital that the negotiating parties have no misunderstanding of the terms and conditions in the agreements.

Train scheduling is also a challenging task as it depends heavily on the demand from different types of train services (Gibson, Cooper and Ball 2002). For instance, in an attempt to schedule a freight train in a system dominated by passenger services, the capacity utilisation is very likely to be degraded because the slower freight trains often cause delays to the faster passenger trains. To avoid such delays, the freight services are given low priorities of access and may be scheduled at off-peak periods only. On the other hand, when freight service dominates the demand, it is difficult to devise a schedule that efficiently utilises the track capacity due to the ad-hoc service requirement. Although the scheduling process may be simplified by an administered mechanism (Gibson 2003) in which the priority on right-of-way is allocated according to a set of predefined rules, flexibility is largely jeopardised and efficient use of track capacity is not guaranteed. It is thus beneficial to develop a train schedule that can compromise the fluctuating demands of different types of train services while maximising network capacity.

These engineering issues introduce further complications to the optimisation process. First, in addition to the access charge, there are more attributes to be negotiated, such as the type of rolling-stock, arrival and departure times of trains. Second, the existence of engineering constraints implies less flexibility in selecting an optimal solution. Furthermore, these constraints may vary according to the commitment of the stakeholders due to the fluctuation in demand. The resultant problem is therefore a multi-attribute, constrained optimisation problem which is both distributed and dynamic.

Regulatory issues

The intention of regulation after the reforms focuses mainly on encouraging the full utilisation of railway capacity, and the maintenance and development of the network. Although regulations on the pricing structure are still present, they are in general more flexible and they attempt to cause minimal interference to the competitive market.

For instance, there are now two categories of regulations in UK (Office of the Rail Regulator [ORR] 1999). The first one is compulsory, where violations of these regulations will lead to termination of the operating licences. These regulations often form the basic disciplines of the operators (e.g. no collusion between operators and a minimum requirement on maintenance investment). The other type of regulations relates to some incentive targets (e.g. additional subsidies if the railway capacity can be increased), where failing to achieve these targets will not lead to the termination of licences, but if they are attained, rewards will be given to the operator.

These regulatory constraints provide incentives to improve the overall utilisation of resource, rather than allowing the stakeholders to optimise strictly with respect to their commercial objectives. However, it is often difficult to identify the impacts of these regulations since the effects may not appear immediately. Also, the constraints imposed on one stakeholder (e.g. train service provider) may transverse through the chain of interactions to other stakeholders (e.g. infrastructure maintenance companies), and these indirect effects are not easy to identify.

Modelling issues

The resource allocation problem generated from the restructuring process is clearly complex.

Nevertheless, it will be beneficial if a model can be devised to study the effects of adopting different strategies on the management, engineering and regulatory issues.

A model is a representation of the behaviour of a system. If a model can be implemented in a computer executable form, it will be a cost-effective means to study the effects from a given set of input stimuli (Ghosh 1999). In other words, if a suitable simulation model can be devised for the restructured railway system, it will be useful to study a variety of 'what-if' scenarios arising from hypothetical regulations, marketing strategies and train scheduling mechanisms. By comparing the results obtained from these simulations, valuable information can be obtained to improve the operations in the system.

For example, there have been continuous debates on the degree of vertical and horizontal separations in a railway market (ECMT 2001). Despite the expected benefits on improved efficiency resulted from railway competition, over-fragmented railways have been found to experience problems associated with safety issues. Since a large proportion of capital cost is derived from track facilities, if the railway market becomes too competitive, the rate of return for the infrastructure provider may be too slow to provide any incentives for improving or even maintaining the quality of the infrastructure. This leads to the rapid deterioration of the infrastructure facilities and even an increased risk of undesired incidents. As a result, if a suitable computer simulation tool is available, studies on the revenue income can be performed with different degrees of competitions. This helps the railway regulatory bodies to determine the granularity of railway separations and regulate the amount of investment required on maintenance and improvement on the infrastructure.

Unfortunately, it is difficult to model the behaviour of the restructured system by the conventional techniques such as the centralised decision-making models (Carey 1994, Goodman, Siu and Ho 1998, Ho and Yeung 2001). In fact, a suitable model for the restructured railway system should ensure an adequate representation of the distributive nature, negotiation and rational behaviours amongst the stakeholders.

Distributive entities: As a result of the disintegration of the railway systems, the model should be capable of representing the stakeholders as separated entities. In addition, each of them should possess independent control over their decision-making mechanism, actions and information. The restructured system therefore requires a model that is distributive, and each entity in the model should be self-interested to ensure the benefit-seeking behaviour of each stakeholder is captured.

Negotiation: The model is also required to allow the entities to negotiate for attributes associated with the resource, such as price and schedule. The negotiation should provide a means to resolve conflicts arising from dispute over price and engineering constraints. In addition, the model must capture the bilateral (one-to-one) and/or multi-lateral (one-to-many) negotiations between the stakeholders, in order to simulate the supply-chain management and competition requirements. Moreover, whenever a deal is made between the entities, the negotiation strategy should preferably result in a Pareto-optimal solution. This means that any deviations from this solution results in worse payoffs for at least one entity (Ehtamo, Verkama and Hamalainen 1996).

Rationality: The entities need to make rational decisions and take appropriate actions according to the set of management and engineering objectives assigned to them. These entities are equipped with sufficient intelligence to handle the interactions without human interferences. They are also required to be responsive to the dynamic changes in the supply and demand in the system, and they should be able to initiate beneficial activities (e.g. promoting idle resources) to improve the competitiveness of the entities.

Multi-agent systems

A multi-agent system (MAS) is a group of interacting software agents, capable of acting autonomously through communicative acts. Each agent is a representative to a real-world entity (Wooldridge 2002). Agents are generally considered to be self-interested and they only have partial control of the environment. In other words, the actions derived by an agent might not always achieve its objectives, and it needs to be reactive and proactive to adapt to the environment. Reactivity refers to the ability to perceive changes in the environment and respond to them accordingly, while proactivity refers to the ability to exhibit goal-directed behaviour by initiating actions to achieve its designed objectives. In addition, agents should have the ability to interact with each other whenever it is beneficial.

MAS modelling emerged in the 1980s and it is a comparatively new modelling approach. Applications using MAS include e-commerce (Au, Ngai and Parameswaran 2003, Liu and You 2003), business process management (García-Flores, Wang, and Goltz 2000, Jennings *et al* 2000a, b) and engineering control systems (Jennings and Bussmann 2003). In railway engineering, a prototype MAS to dispatch freight trains on a single railway line was developed in Italy (Cuppari, Guida, Martelli, Mascardi and Zini 1999). Later, the MAS technology was applied on optimising the train coupling and sharing system (Böcker, Lind and Zirkler 2001). In these applications, MAS allowed the complex systems to be organised as a community of well-defined entities. In addition, it permits agents to exhibit intelligent behaviours such as reactivity, proactivity and social capabilities through the modelling of classical or AI techniques (Krishna and Ramesh 1998a, b, Faratin, Sierra and Jennings 2002, Luo, Jennings, Shadbolt, Leung and Lee 2003)

The development of MAS often requires careful design and implementation. Two of the major problems associated with MAS design are the decisions on the size of the agent community and the models of agents' intelligence (Wooldridge and Jennings 1999). As an example for the former, a system could have only one layer of agents to represent the companies in a supply-chain, while it is also possible to expand two more layers for the departments in the companies and the staff in the departments. The three-layered approach clearly requires a higher demand in modelling the autonomy and interactions of the agents, but more detailed studies can be performed at the department level and the personnel level. The granularity of the agent society thus depends on the depth of study required. For the latter, it is easy for the designers to overlook the existence of simpler and more efficient classical techniques and implement AI models directly. In fact, the choice of models for the rational activities in an agent is highly application-specific. Despite the increasing number of applications using MAS, there are no standardised techniques in constructing an agent system. In other words, thorough studies are needed to verify the performance of the MAS for a specific application.

Realisation of MAS in restructured railway

A realisation of MAS for railway resource management is illustrated in Figure 2. Only one level of agents is implemented to allow studies of the interactions between the stakeholders. It

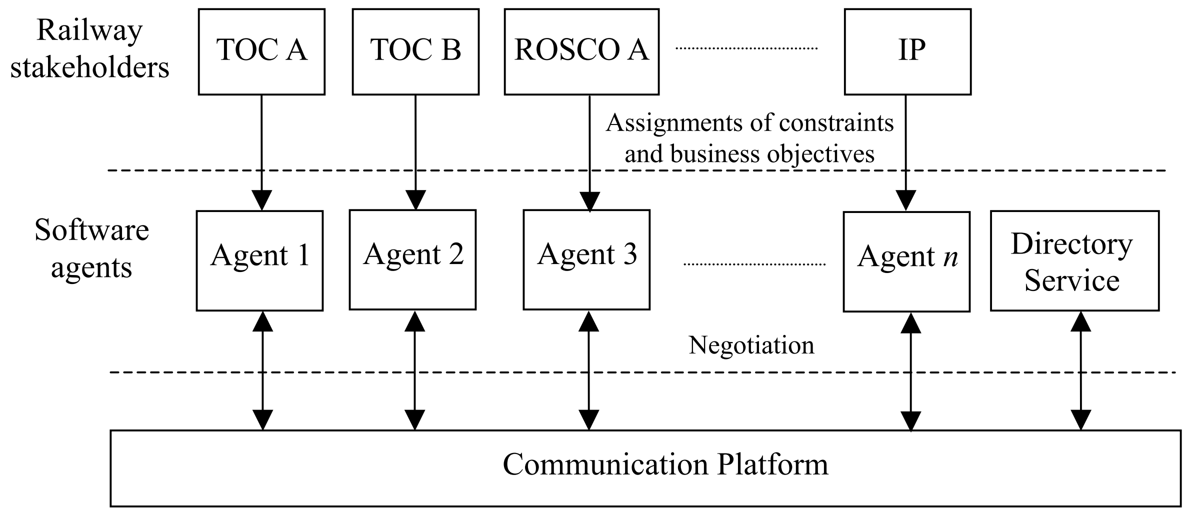

Figure 2 MAS for the restructure railways

is assumed that the departments and personnel within a stakeholder company share the common goals. Using this architecture of MAS, it is worth examining the feasible studies allowed to help the railway stakeholders to manage their resources efficiently.

Distributed autonomy: In this architecture, the infrastructure provider, train serviceoperators and the supporting utilities are represented by different agents. Since agents are autonomous, they are self-contained entities, each of which encapsulates the assigned confidential information such as cost curves and operational tactics. Other agents in the community only perceive the agent as a resource provider or a purchaser. In addition, these agents are not expected to share a common goal, but they may form temporal association to examine whether a sale of resource is feasible and beneficial. This agent community can be used to study the effects from different degrees of competition by changing the number of resource providers and/or purchasers.

Communication capabilities: Agents can be programmed to negotiate with other agents and form contractual agreements according to the assigned criteria of the stakeholders. In order for an agent to recognise the existence of other agents and resources that they provide, a communication platform with a directory service is needed. Two or more agents should be allowed to participate in the negotiation process. Studies should aim for identifying the Pareto-optimal solution. Currently in the agent literature, the available negotiation mechanisms are based on fuzzy logics (Luo *et al* 2003) and probability theory (Krishna and Ramesh 1998a, b). Owing to the application-specific nature of MAS modelling, direct incorporation of these strategies may not be applicable. It is however desirable to study how they could be extended in the restructured railways.

Rationality: Further studies will also be performed to evaluate the impacts from any hypothetical changes in regulations, business objectives and engineering operations by modifying the rational behaviour of the agents. For instance, constraints as a result from regulatory changes can be added locally to the relevant agents, and modification on business objectives and scheduling mechanism may be achieved by adjusting the internal cost functions and implementing a proper model respectively. Results from these simulations will be used to improve the capacity utilisation or the competitiveness of the stakeholders.

Implementation of MAS in restructured railway

A train service provider (SP) agent representing a TOC in Figure 2 has recently been modelled and developed by a Prioritised Fuzzy Constraint Satisfaction (PFCS) approach (Tsang and Ho 2004). The SP agent is able to negotiate autonomously with an infrastructure provider (IP) for a simple train schedule consisting of an access charge, arrival and departure times, and types of rolling-stock. The TOC's preferences over the access charge and schedule times are modelled as fuzzy constraints with different priorities while that of the rolling-stocks are modelled by a set of preference values indicating the degree of satisfaction by the TOC. When the SP agents are assigned with different priorities and preference values, the agents are shown to exhibit rational behaviour that is consistent with the assigned objectives (e.g. cost-cutting-oriented and service-quality-oriented). This supports that the MAS modelling approach is feasible to model the stakeholders in the restructured environment. Nevertheless, in order to further demonstrate that the proposed model can indeed allow the railway industry to conduct more sophisticated studies described in this paper, development of models for agents of other stakeholders and their associated intelligence is essential.

Conclusions

We have described the effects of vertical and horizontal separations in railways. The process resulted in a community of stakeholders who compete for providing and acquiring for railway resources. The behaviour of the stakeholders in such a competitive market becomes a distributed, multi-attribute, constrained and dynamic optimisation problem.

MAS modelling is a natural means to capture the distributed nature of the system. Each stakeholder in the system can be represented by a software agent. These agents seek for solutions according to the assigned criteria and dynamic situation of the environment. Extensive studies can be undertaken to investigate the effects of various degrees of competitions and hypothetical changes on regulations, business objectives, and engineering constraints. However, such MAS model requires a delicate balance on the size of the agent community and the complexity of inter-agent interactions. Moreover, proper models of the agents' intelligence are highly application-specific and thorough studies are needed to verify their feasibilities and limitations.

A MAS model for railway resource planning has been proposed. The granularity of the model focuses on the behavioural studies of the stakeholders, rather than the internal interactions with the individual organisation. A pioneer study is referenced on using a PFCS approach to model the negotiation behaviour of a SP agent for a train schedule with an IP. The study found that by modifying the preference values assigned to the agents, the agents' behaviour can be adjusted so that it is consistent with the assigned objectives. Despite the lack of applications in supporting the feasibility of the proposed model, the current results do show promise for further research opportunities.

This paper forms part of broader research on formulating a MAS model on railway resource management under the restructured environment. It is expected the major difficulty during the development is the identification of suitable models for representing the intelligence of the agents. Additional studies are therefore required to verify the efficiency of an agent based on a particular model. However, while the ultimate direction of research is to develop a complete

MAS system, the short-term research should focus on creating the platform for negotiation, and examining the suitability of the current agent negotiation mechanisms for the existing railways. It is also the intention of this paper to encourage and enhance the recognition of the potential advantages of MAS applications in railway engineering.

Acknowledgements

The authors wish to thank the Department of Electrical Engineering of the Hong Kong Polytechnic University for the financial assistance.

References

Au, S Ngai, E and Parameswaran, N (2003) ECAN: an agent assist e-commerce trading platform, pp. 482–493 of *Proceedings of the 2003 International Conference on Intelligent Agents, Web Technologies and Internet Commerce*, Vienna

Australian Rail Track Corporation Limited [ARTC] (2002) *Access Undertaking version 4* (30 April 2002)

Böcker, J Lind, J and Zirkler, B (2001) Using a multi-agent approach to optimise the train coupling and sharing system *European Journal of Operational Research 131* (2), 242–252

Carey, M (1994) A model and strategy for train pathing with choice of lines, platforms, and routes *Transportation Research Part B 28* (5), 333–353.

Crompton, G and Jupe, R (2003) "Such a silly scheme": the privatisation of Britain's Railways 1992–2002 *Critical Perspectives on Accounting 14* (6), 617–645

Cuppari, A Guida, P L Martelli, M Mascardi, V and Zini, F (1999) Prototyping freight trains traffic management using multi-agent systems, pp. 646–653 of *Proceedings of the 1999 International Conference on Information Intelligence and Systems*, Maryland: IEEE

Department of the Environment, Transport and Region [DETR] (1998) *Focus on Freight* London: The Stationery Office

Department of Transport and Regional Services [DOTARS] (2002) September 20 – last update [Online] Available: *http://www.dotars.gov.au/transreg/str_history.htm* [2004, February 2]

European Conference of Ministers of Transport [ECMT] (2001) Railway reform: regulation of freight transport markets *SourceOECD Transport 2001* (1), 1–135

Ehtamo, H Verkama, M and Hamalainen, R P (1996) On distributed computation of Pareto solutions for two decision makers *IEEE Transactions on Systems, Man and Cybernetics Part A 26* (4), 498–503

Faratin, P Sierra, C and Jennings, N R (2002) Using similarity criteria to make issue trade-offs in automated negotiations. *Artificial Intelligence 142* (2), 205–237

García-Flores, R Wang, X Z and Goltz, G E (2000) Agent-based information flow for process industries' supply chain modelling *Computers & Chemical Engineering 24* (7), 1135–1141

Ghosh, S (1999) Fundamental issues in intelligent transportation systems *Proceedings of the I MECH E Part F 213* (2), 125–131

Gibson, S Cooper, G and Ball, B (2002) The evolution of capacity charges on the UK rail network *Journal of Transport Economics and Policy 36* (2), 341–354

Gibson, S (2003) Allocation of capacity in the rail industry *Utilities Policy 11* (1), 39–42

Goodman, C J Siu, L K and Ho, T K (1998) A review of simulation models for railway systems, pp. 80–85 of *Proceedings of the International Conference on Developments in Mass Transit Systems* London: IEE

Ho, T K and Yeung, T H (2001) Railway junction traffic control by heuristic methods *IEE Proceedings – Electric Power Applications 148* (1), 77–84

Krishna, V and Ramesh, V C (1998) Intelligent agents for negotiations in market games – part 1: model *IEEE Transactions on Power Systems 13* (3), 1103–1108

Krishna, V and Ramesh, V C (1998) Intelligent agents for negotiations in market games – part 2: application *IEEE Transactions on Power Systems 13* (3), 1109–1114

Jennings, N R Norman, T J Faratin, P O'Brien, P and Odgers, B (2000) Autonomous agent for business process management *Applied Artificial Intelligence 14* (2), 145–189

Jennings, N R Faratin, P Norman, T J O'Brien, P Odgers, B and Alty, J L (2000) Implementing a business process management system using ADEPT: a real-world case study *Applied Artificial Intelligence 14* (5), 421–463

Jennings, N R and Bussmann, S (2003) Agent-based control systems: why are they suited to engineering complex systems? *IEEE Control Systems Magazine 23* (3), 61–73

Jensen, A (1998) Competition in railway monopolies *Transportation Research Part E 34* (4) 267–287

Liu, J and You, J (2003) Smart shopper: an agent-based web-mining approach to internet shopping *IEEE Transactions on Fuzzy Systems 11* (2), 229–237

Luo, X Jennings, N R Shadbolt, N Leung, H and Lee, J H (2003) A fuzzy constraint based model for bilateral, multi-issue negotiations in semi-competitive environments *Artificial Intelligence 148* (1), 53–102

Office of the Rail Regulator [ORR] (1999) *The Periodic Review of Railtrack's Access Charges: The Incentive Framework – a Consultation Document*

Shaw, J (2001) Competition in the UK passenger railway industry: prospects and problems *Transport Reviews 21* (2), 195–216

Strategic Rail Authority [SRA] (2003) July 1 – last update [Online] Available: *http://www.sra.gov.uk/qa/service.tt2* [2004, February 2]

Tsang, C W and Ho T K (2004) A Prioritized Fuzzy Constraint Satisfaction Approach to Model Agent Negotiation for Railway Scheduling, accepted in *Proceedings of the International Conference on Machine Learning and Cybernetics 2004* Shanghai: IEEE

Watson, R (2001) The effect of railway privatization on train planning: a case study of the UK *Transport Reviews 21* (2), 181–193

Wooldridge, M (2002) *An Introduction to Multiagent Systems* Chichester: John Wiley

Xie, R Chen, H and Nash, C (2002) Migration of railway freight transport from command economy to market economy: the case of China *Transport Reviews 22* (2), 159–177

Xue, X Schmid, F and Smith, R A (2002) An introduction to China's rail transport – part 2: urban rail transit systems, highway transport and the reform of China's railways *Proceedings of the I MECH E Part F 216* (3), 165–174