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Improving productivity of road surfacing operations using value stream mapping and discrete event simulation

Zeeshan Aziz, Rana Muhammad Qasim and Sahawneh Wajdi
School of the Built Environment, University of Salford, Salford, UK

Abstract

Purpose – The purpose of this paper is to investigate the integration of discrete event simulation (DES) and value stream mapping (VSM) to enhance the productivity of road surfacing operations by achieving high production rates and minimum road closure times. Highway infrastructure is one of the most valuable assets owned by the public sector. The success of national and local economies as well as quality of life of the general public depend on the efficient operations of highways. Ensuring smooth traffic operations requires maintenance and improvements of the highest standard.

Design/methodology/approach – Research approach involved the use of primary data collected from direct observation, interviews, review of archival records and productivity databases. Based on this, process maps and value stream maps were developed which were subsequently used to produce discrete event simulation models for the exploration of different optimisation scenarios.

Findings – This research highlights the synergistic relationship between VSM and DES in driving innovation in construction processes. Identified factors that affect roadworks process productivity include machine, manpower, material, information, environment and method-related factors. A DES model is presented to optimise the process and increase the production rates. A hybrid DES-VSM approach ensures an integrated approach to process optimisation.

Research limitations/implications – This study is an application of hybrid version of previously published DES-VSM framework in the manufacturing sector. The present study has extended and tested its applicability within road surfacing operations. The different what-if scenarios presented in this paper might not be applicable to other parts of the world owing to various constraints. The study has focused on addressing the waste production inherent in pavement laying process. Even though external variables could possibly influence pavement process, those were ignored to allow for in-depth focus on the process under consideration.

Practical implications – Road users are one of the most important stakeholders that will benefit from the positive implications of this study. Private resurfacing companies and transport departments can optimise their overall process and style of working by comparing their end-to-end process and work plans with the ones mentioned in this paper. It will boost the productivity of equipment like planners, pavers and other machines used for resurfacing operations.

Originality/value – Existing approaches to process modelling such as VSM and process diagrams are constrained by their effectiveness in the analysis of dynamic and complex processes. This study presents a DES-based approach to validate targeted improvements of the current state of road surfacing processes and in exploration of different optimisation scenarios.

Keywords Productivity, Simulation, Process improvement, DES-VSM framework, Paving, Road Surfacing

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1. Introduction

Road surfacing is an important component of highway development and maintenance. Highway construction sector, in general, is characterised by its slow pace of change, low productivity, waste, fragmentation and long-established processes and ways of doing business which has not changed over decades. Efficient running of road network has the success of national and local economies as well as the quality of public life dependent on it. Increasing volumes of traffic require maintenance and improvements of the highest standard. For instance, the National Infrastructure Plan (NIP) by HM Treasury, United Kingdom (2015), has detailed the existing commitments leading to the construction of at least 52 major road projects by 2020-2021, addition of over 750 lane-miles of capacity to the busiest motorways and trunk roads and resurfacing of about 80 per cent of the strategic road network (SRN) by 2020. Such huge public-sector investments in road infrastructure come alongside the government's cuts in operations and maintenance expenditures on infrastructure owing to macroeconomic challenges facing the economy. Thus, a key challenge is to deliver major road schemes in resource-constrained environments while maintaining safety, cost efficiency, sustainability and minimal impact on road users. Enhancing the productivity of existing processes is the key to successfully operating in a resource-constrained environment.

Recent reviews of the construction productivity performance, specifically roadworks, indicate that the industry has fallen short in comparison to manufacturing- and services-based industry sectors. Some of the key factors restraining the productivity of construction are related to quality, use of project controls and proper levels of supervision. Similar observations were made in the annual UK Construction Industry Performance Report (2015), indicating that majority of construction projects continue to fail to meet their time and cost targets. These observations are often coupled with falling profitability and client dissatisfaction with regards to product quality, service and value for money. As explained by Jergeas (2009), excessive time extensions, over budgeting and lack of productivity are connected with the conduct of major capital construction projects worldwide. Several researchers and practitioners have recognised poor management practices that cause poor performance, namely, scope changes, lack of proper planning and scheduling, design errors and omissions, inadequate management of tools, equipment, materials and labour, in addition to many other factors. Resulting road closures result in negative feedback from road users.

Considering the aforementioned findings, there is an urgent need for improving the productivity of roadworks projects within the construction industry to deliver ongoing and future projects with maximum efficiency and minimum waste. To address the issue of efficiency, various opportunities have been realised in the highway sector. Discrete event simulation (DES) coupled with value stream mapping (VSM) has been recognised as a technique to improve the overall process as well as some specific key areas. Manufacturing, process, construction and healthcare sectors have advanced their processes and benefitted from either simulation, VSM or the integration of both.

The rest of the paper is organised as below. Section 2 presents a literature review, while Section 3 introduces readers to the analysed case study. Section 4 introduces different scenarios of DES model. This is followed by discussions in Section 5 and finally the conclusions.

2. Literature review

Literature review discusses the relationship between DES and VSM, how they both complement each other and the relevance of the relationship in supporting highway operations. The synergic relationship between VSM and DES has been tested and applied before in manufacturing and construction industry. However, its usage in resurfacing and asphalt industry has not been adequately explored. Table I presents a summary of key previous literature published within the road resurfacing context. Published literature focuses on the logistics involved in resurfacing operations and does not adequately cover the hybrid VSM-DES relationship in resurfacing of road pavement.

VSM was formed using Toyota production system and lean manufacturing principles (Womack *et al.*, 1990). It is defined as an iterative method used to map and analyse value streams, and its goal is to evaluate and communicate production process aspects such as material and information flows, as well as non-value-adding actions (Rother and Shook, 2003; Lasa *et al.*, 2008). It is used in improvement schemes like increasing throughput and in reducing the lead time and work in progress (WIP) (Alvarez *et al.*, 2009). VSM is made up of three components:

(1) Current State Gap that visualises value-adding and non-value-adding activities in a process;

(2) Future State Design, a value stream that solves the identified problems of current state; and

(3) Yearly Value Stream Plan that creates an operational plan to reduce the gap between the present and future states (Martin and Osterling, 2014).

VSM, however, cannot provide hard facts for decision making and simply points towards a direction. It lacks the ability to forecast the effects on future performance of a system analytically. Hence the need for simulation arises to experiment and evaluate the future behaviour of a scheme (Erikshammer and Weizhuo, 2013). Basic lean tools, including VSM, are sufficient for analysing simple and linear processes with relatively consistent demand patterns. Static approaches are incapable of analysing processes that incorporate volatile demand dynamics, mixed product complexity or the shared use of resources. In such scenarios, time dependencies are important as a process simulation model can accurately describe and visualise the dynamics of the process, its performance and the required resources.

Simulation is the process of modelling a real-world situation and developing a framework within which the system can be analysed (Law and Kelton, 2000). Application of simulation in construction operations has many advantages including estimation of possible delays, productivity determination and improvement, in addition to resource management and optimisation, stochastic system response to unexpected conditions and ability to respond to random and dynamic features while the system is operating (Halpin, 2003). Simulation is also defined as a “controlled statistical sampling technique (experiment) that is used, in conjunction with a model, to obtain approximate answers for the question about complex, multifactor probabilistic problems” (Lewis and Orav, 1989). This technique is used by many industries to model real-life and hypothetical situations, owing to its dynamic nature and complex scenarios. This was also acknowledged by Bhasin, 2015, stating that as an integral part of a lean activity, companies spend much time designing new process layouts, producing CAD drawings and building process maps en route. The cost of these activities can run into significant amounts even when none of these outputs will indicate whether the new process will succeed. That is the job of process simulation, which can examine the capability of the new design and provide vital implementation support to decision makers that they are on the right path.

The integration of VSM with DES is more dominant in manufacturing industry than in construction. Simulation-based VSM makes it possible to investigate complex systems and

Table I. Synergistic relationship between DES and VSM and its popular applications

References	Industry	Findings	DES	VSM	DES-VSM framework
Marzouk and Fouad (2011)	Highways, Resurfacing	This paper only uses simulation for improvement in traffic flow while resurfacing happens under lane closure condition. It does not mention VSM or the holistic view of overall process	✓		
Xie and Peng (2012)	Healthcare	Integration of simulation and VSM can analyse alternatives for problems of capacity planning and schedule control and improve healthcare operations			✓
McDonald *et al.* (2002)	Manufacturing	DES can be a vital part of VSM to complement future design			✓
Lian and Van Landeghem (2007)	Manufacturing	Integration of DES with VSM improves information for process design			✓
Agyapong-Kodua *et al.* (2009)	Manufacturing	Transforming static VSM models to dynamic DES increases validity and reliability of future design			✓
Marvel and Standridge (2009)	Manufacturing	DES provides validation and visualisation of VSM future design			✓
Singh and Sharma (2009)	Manufacturing	VSM is a powerful tool for lean manufacturing and allows firms to continuously improve their understanding of lean processes		✓	
Yu *et al.* (2009)	Construction	Combination of DES and VSM increases understanding of behaviour of future design			✓
Gurumurthy and Kodali (2011)	Construction	DES validates, approves and visualises VSM future design			✓
Erikshammer and Weizhuo (2013)	Construction	VSM is unable to analytically evaluate performance of future state design without the help of DES			✓
Labban and Haddad (2013)	Construction	Although research into simulation of construction continues to advance and thrive in the academic world, application of simulation in the construction industry remains limited	✓		
Abdulmalek and Rajgopal (2007)	Process	Data obtained from DES evaluates and validates VSM process design			✓
Seth *et al.* (2008)	Process	VSM serves as a starting point to help management, engineers, suppliers and customers recognise waste and its sources		✓	

interpret the simulation results in a language that lean recognizes (Solding and Gullander, 2009). Both DES and VSM provide a holistic assessment of a system, and DES also adds a fourth dimension, time, to VSM. This combination offers insights that may have been missed if VSM alone had been used (Donatelli and Harris, 2009). It has been noticed that DES can enhance VSM and a process can benefit incredibly with the integration of both (Erikshammer *et al.*, 2013). The main purpose of using their integration is to boost the productivity of resurfacing process, reduce waste and maximise the efficiency of resources involved in the process.

Productivity is described as the ratio of outputs to inputs used in the production process. In other words, it is the output per input unit. Slitherers (2009) described productivity in the manufacturing industry as a "measure of the output compared to the input". However, productivity in construction can be defined in terms of many factors such as performance, productivity rate and unit person-hour (p-h) (Dozzi and AbouRizk, 1993). A definition of productivity in the construction industry was presented by Merrow *et al.* (2009), using three approaches: the economic approach, a construction manager's approach, and the project approach. The economics approach measures labour productivity regarding the economic output per hour worked. The construction manager's approach measures productivity at activity level by determining the work done per hour at the team or individual level. Finally, the project approach measures the productivity of the entire project as a unit of observation. Dozzi and AbouRizk (1993) stated that productivity has two significant measures which are the efficient use of labour and the relative competency of labour to achieve what is required; the latter is the most important to contractors and organised labour. Rebholz *et al.* (2004) defined productivity in road construction industry as the quantity of laid asphalt in tonnes per hour or per day. For purposes of this study, this definition was adopted.

3. Methodology

The key focus of this effort was improving the productivity of the road surfacing process. The study drew upon lean theory and tools to improve road resurfacing operations. There are approximately 40 lean tools that are being used in diverse operations worldwide, and they all have different styles of operation. Some of the common tools are 5s, Andon, Last planner, Single Minute Exchange of Dies (SMED), Kanban, VSM, process mapping, visual management and Kaizen. This study, however focused on VSM and attempted to improve and validate it with a simulation technique. The reason for choosing VSM was its frequent application in highway operations. VSM is used to visualise and map the processes leading to the attainment of high production levels. However, as mentioned in the literature review, there are various weaknesses and drawbacks of VSM that can be eliminated through the application of DES. The gaps and loopholes in value stream maps of resurfacing operation were diagnosed with the help of fishbone analysis.

For validation of VSM, a simulation technique was adopted. The main three types of simulation are *discrete-event, continuous and Monte-Carlo*. They were defined by Nance (1993) as *discrete event simulation (DES*), which uses a logical model of a real-life physical system representing state changes at precise points of the simulated time. Both the nature of the state change and the time at which the change occurs dictate an accurate description. A *continuous simulation,* which is based on the equational model, rarely represents a real-life system and does not represent the precise time and state relationships arising in discontinuities. The objective of researches conducted using such models has no requirement for the explicit representation of state and time relationships. A *Monte-Carlo simulation*, which uses models of uncertainty and representation of time, is required. The term originally attributed to a situation in which a difficult non-probabilistic problem is simulated through the presentation of a stochastic process satisfies the relations of a deterministic problem.

For the purpose of this study, DES was chosen because of the flexibility and precise state fluctuation within the process. While multiple DES software applications have been introduced into the market by different developers, such as *FlexSim, Simio, Anylogic, JaamSim, MASON, Sim.JS* and many others, *FlexSim* was selected to carry out the intended simulations considering it is one of the most popular simulation software applications for its ease of use, rich functionality and capabilities of tracking different data points such as throughput, content, machine state and utilisation. According to Manuj *et al.* (2009), there are seven major steps in the methodology of creating a simulation of a real-life situation of a system:

3.1 Problem formulation

This step involves defining overall objectives and answering questions specific to the simulation model. According to Keebler (2006), this is a critical step, and lack of attention in this phase can lead to let-down in model's performance. If the problem is not stated precisely or in quantifiable terms and the purpose is ambiguous, it will lead to time wastage, incorrect analysis, unfitting decisions and incorrect inferences (Dhebar, 1993). It is a good exercise to consult individuals who are involved in the problem to address it properly. It will not only help in defining the scope but also aid in establishing the key performance indicators (KPIs), time limits and required resources.

3.2 Selection of dependent and independent variables

Dependent variables show the performance measures, and independent variables include the system parameters. Independent variables are manipulated, and their effects on dependent variables are logged and investigated in a simulation model. The values of dependent variable provide answers to the problem formulated in Step 1. As the outcome of a model depends on what is included in it, the objective of the research and specific questions guide the selection of dependent and independent variables. Various variables can influence the simulation, including legal, technical, economic, organisational, managerial, monetary and historical factors (Towill and Disney, 2008).

3.3 Development and validation of conceptual model

According to Banks (1998), a conceptual model is an abstraction of the real-life system under examination. It uses logical and mathematical relationships related to the components and structure of system. Unambiguous assumptions and specified descriptions in the conceptual model ensure that the model is developed in accordance with the problem statement. The validity of the outcomes directly depends on the inputs in the system, and therefore, it is important to develop a conceptual model for validation prior to investing resources in a computer-based model.

3.4 Data collection

This step can be challenging as data might not be readily available or in required formats. Sometimes the level of detail is inappropriate and this step is performed in parallel to the development of the conceptual model. Data requirements must be established first to define system parameters, layout, probability distributions and operating procedures. Data can be obtained from company databases, surveys, interviews and other published sources. In some cases, data can be generated using a computer if the actual data can be approximated using distributions like Poisson, normal and exponential methods. Theses data are the backbone of the whole work, and any mistakes in this step will nullify all further analysis.

3.5 Development and verification of computer-based model

Computer modelling begins simply, and complexity can be added in steps until a model of adequate detail and complexity has been created (Banks, 1998). Verification is performed to check whether the computer application of the conceptual model is correct. According to Sargent (2007), verification is a continuous process, and it needs to be performed concurrently with the development of the computer model rather than at the end. Verification means analysis of outputs, debugging of errors and checking the code. There are two benefits of verification:

(1) identification of undesirable system behaviour; and
(2) checking whether the complex steps can be replaced with simpler ones (Fishman and Kiviat, 1968).

Various software are available in the market to create and verify a simulation model.

3.6 Model validation

Model validation is a process of establishing whether a simulation is accurately representing the system under investigation. This validated model can then be used to make decisions similar to what the system could perform if they were feasible and economical to experiment (Law, 2006). An invalid model cannot be trusted as it may lead to erroneous conclusions. There are various ways to validate a model, including consulting academic scholars and practitioners, focus group interviews and performing sensitivity analyses.

3.7 Simulations

At this stage, various scenarios are run in the simulation with changing dependent and independent variables. For each system configuration of interest, decisions are made on the number of independent model replications, size, warm-up period and run length. In a simulation, sample size can be increased by increasing the number of simulation runs for each condition, reducing the length of subintervals and increasing the length of the run to increase the number of subintervals (Bienstock, 1996).

A similar method is used in this study. However, what differentiates this study from other works is the use of VSM. The figure below shows the methodology used for the creation of conceptual framework, verification, data collection, development and validation. Figure A1 shows the framework developed for this particular work.

4. Case study analysis

This section presents a detailed case study of a road surfacing process improvement project at the project level, involving the use of lean tools alongside DES to explore the opportunities of optimising the existing road surfacing process.

All types of roadwork processes, whether new constructions or maintenance work, are classified into two major types, i.e. surfacing and resurfacing. Every road surface has its diverse characteristics which vary according to its geography, location, surrounding terrain, speed-related parameters, intended use and type of pavement. A typical comprehensive resurfacing process of a hot mix asphalt pavement is shown in Figure A2 (Area 9 Pavement Process Improvement, 2015). Key constraints that must be addressed before the start of pavement process include setting up of traffic management system (typically 15 min), material call-off and planner mobilisation (typically 30 min) and planning a head start (typically 45 min), leading to a total non-value-adding, pre-paving time of 1 h 30 min. Key post-pavement process constraints include rolling (typically 30 min), cooling and curing (typically 75 min) and traffic management system removal (typically 30 min). This means a total of 2 h and 15 min post-paving shift period. A safety margin of around 1 h 30 min is set for safety-related activities. Installation and removal of traffic management system has an average duration of 30 to 45 min and depend on a wide range of variables including the use of different designs and types of traffic management systems, delays and operator-/process-related variables.

Analysis of archived data and that collected from on-site observation was used to build a situation summary and current state of the process as discussed below:

(1) The average output for a paving team is 240 tonnes per shift.

(2) A paver can lay 130 tonnes per hour when it is operational. This equates to 1.8 h of value-adding activity in a typical shift (240 t/130 t = 1.8 h of value-adding work).

(3) Utilisation of plant and people based on a 10-h paid shift:
   - Planning team: 137/600 min = 22 per cent utilisation;
   - Sweeper (same as planning above) = 22 per cent utilisation;
   - Spraying (nominal utilisation as this is a very quick operation);
   - Paving team utilisation = 108/600 min = 18 per cent utilisation;
   - Rolling (same as paving above) = 18 per cent utilisation;
   - White lining = 60/600 min = 10 per cent utilisation;
   - Trucks removing planning and delivering blacktop = 30-40 per cent; and
   - Aggregate plant = circa 20-40 per cent utilisation.

(4) Eighty-six per cent of the time paving teams work within a 7-8-h work window.

(5) Fourteen per cent of the time paving teams work in excess of this window: between 9 and 10 h.

(6) There is an average 23-min delay between the placement of a traffic management system and the start of the first value-adding activity.

(7) Analysis of past six months data indicates that the total paving activity (plane, pave, sweep, spray and roll) take up approximately 3 h 54 minutes or between 50 and 57 per cent of the available work window.

Figure A2 shows the "As-Is" process as a bar chart based on data observed at two site visits and supported by historical data. Key value-adding activity (i.e. paving process) ran for just 2 h 11 min in an 8-h work window (10 p.m. to 6 a.m.) and 10-h worker shift (9 p.m. to 7 p.m.). A total of 298 tonnes over a stretch of 938 m was laid in 2 h 11 min of value-adding activity, leading to an hourly tonnage rate of 137 T and pavement productivity of 33 per cent. While the work window was up to 6 a.m., the traffic management system was removed at 4:39 a.m., leading to 1 h 29 min' lesser utilisation of the allocated work window.

Figure A3 above shows the value stream map of the as-is operation. Based on it, various opportunities for waste reduction can be identified. Firstly, planning operation started at 22:37 when site access had been granted at 22:08, signifying a delay of 29 min. Secondly, main value-adding activity, i.e. paving, started at 00:17. This highlights a paver sitting idle for over 2 hours, awaiting material arrival. Thirdly, while the work window was up to 6 a.m., workers were off-site about 1 h 21 min before the allocated period, highlighting another area for improvement. Finally, there was a possibility of extending the work window by obtaining an early access to work. Figure A4 below shows the as-is (baseline) process with respect to time.

4.1 Identification of problems

In the problem definition phase, several collaborative workshops and meetings were held with all key project stakeholders involved in the process. Using a team-based approach, various process optimisation opportunities were discussed, key findings from the research were discussed, key constraints affecting the output were analysed, and opportunities for improvement were identified. A key challenge considered by the team was to increase the output and production rates without the deployment of any additional resources. This was done primarily by addressing constraints that primarily affect the flow of work. Improved productivity was to be achieved whilst addressing key constraints of safety (for both operatives and road users), resource wastage (e.g. ordering aggregate materials earlier than usual also increases the risk of material wastage if work is abandoned because of road accident or weather), quality (e.g. increasing paver speed to enhance productivity could have negative consequences for quality), on-time traffic management system removal (to avoid risks of late road openings of busy roads) and operative staff buy-in (in terms of longer working hours and different working methods).

4.2 Steps taken

To reduce time wastage between motorway closure and the start of planning operation, various opportunities for improvement were identified. First, by enabling an early contact between regional traffic control centres helped speed up the process and reduce the waiting time involved in the clearance process. The second area of improvement identified was to set out the traffic management system to close two lanes earlier (given safety constraints are addressed) and bring plant material ahead of full closure. This ensured that plant material was available ahead of full motorway closure. To increase the productivity of pavement process, calling material earlier would allow the paver to begin operations early. There was a time lag of 14 min between the commencement of planner and paver processes, allowing time for cleaning and preparation.

The third area of improvement involved early removal of traffic management system with workers going off-site by 4:39 a.m. There is scope to make the best use of work window by ensuring work continues close to 6 a.m., the allocated work window. Given the fact that paver utilisation in an average shift is just 33 per cent, doubling pavement productivity by addressing constraints (e.g. earlier mobilisation of paver, full utilisation of work window) has the potential to double the paver productivity and, thus, the output. Also, the possibility of extending the work window, particularly over weekends or public holidays, when lesser than average traffic volumes are expected could provide an opportunity to increase productivity. An improved work diagram is shown in Figure A5. It shows an increased work window of 10 hours and 36 minutes. The total asphalt tonnage laid was 1,024 tonnes, in comparison with 298 tonnes laid in the baseline process (Figure A4).

Table II above shows the differences in efficiency between baseline and improved process state. In resurfacing operations, paving is the most important activity, and its duration can highly impact the productivity. It can be seen that paver productivity increased from 33 to 64 per cent leading to 2,700 m of the paved road compared to 938 m on average.

4.3 Data collection for simulation

At this stage, an improvement scheme was implemented, and there was an opportunity to record the data required for the development of the simulation model. Data was required from various times and levels (e.g. present-day data, traffic counts, historic data from aggregate industries, trucks and other equipment data). Most of the process-related information was captured by people present on site in the form of videos and time lapse pictures. This information was then fed to the simulation for better accuracy and validity. Figure A6 below shows the data collection steps and procedures that were required for the development of this simulation model.

4.4 Root cause analysis

This section presents a root cause analysis from six different perspectives, with an end objective to improve the total production per shift. Figure A7 helps understand the current issues facing a surfacing operation system as well as provides project strategy ideas to improve the output. A fishbone (Ishikawa) diagram shows many constraints, identified in the road surfacing process review, and their causes. The fishbone diagram was chosen because of the need to study and analyse the possible reasons that can negatively affect the process output target. The four W's need to be answered and considered to analyse the fishbone diagram. "What" refers to questions related to objects such as materials and machines. "Why" is used to answer questions regarding work conditions such as motivation of manpower. "When" refers to problems related to time sequence in operation such as time needed for production. Finally, "Where" is concerned with effects related to the place, production line, loading area and so on. Figure A7 shows the different factors that were regarded as constraints and were considered responsible for low productivity.

4.4.1 Materials. Key raw materials included asphalt and aggregate. Key risk factor was reliance on a single supplier. Having an alternative supplier list provides more flexibility. Another constraining factor is the aggregate plant capacity, which also can have a major effect on the aggregate supply required to reach the target outputs. Other factors contributing to the production output include the availability of trucks to deliver materials and the number of deliveries they can make.

4.4.2 Machines. Machines refer to the equipment, technology and tools required to perform the process. During road surfacing, many machinery and tools are used, such as paver, roller, planner and pitch spraying machine. Following are some of the identified risks associated with machines:

- the capacity of the aggregate plant is limited to the night-time work window it needs to operate within;
- changeover times within the laying process can have a big impact on the output;
- machines can suffer breakdowns and need maintenance periodically during the laying process; and
- set up of any machine if not performed before material delivery will create a delay in the process.

Processes	Baseline process	Improved process
Shift duration	10 h	10 hours (staggered)
Work window (Theoretical)	8 h (22:00 to 06:00)	13 hours (20:00 to 9:00 a.m.)
Work window (Actual)	6 h 31 min (22:08 to 04:39)	10 hours 36 minutes (21:03 to 7:39)
Tonnage laid	298 tonnes	1024 tonnes
Paving duration	2 h 11 min	6 h 50 min (22:15 to 5:05 a.m.)
Average hourly tonnage laid	137 tonnes (@45-mm thin surfacing)	149 tonnes (@45-mm thin surfacing)
Pavement length laid (in meters)	938 m	2,700 m
Paver productivity (i.e. Paving Time/Full Working time)	33 (%) (2 h 11 min/6 h 31 min)	64 (%) (6 h 50 min/10 h 36 min)

Table II. Improvement comparison

4.4.3 Manpower (people). Site operatives need to have an adequate intellectual and physical capacity to cope with long duration shifts, varying from 8 to 13 h. Moreover, paving operations require high attention to details such as alignment of the asphalt truck to the paver. Furthermore, operator's reliability is necessary to perform the process without errors. In this context:

- shift patterns can be a limiting factor;
- since the working window was extended, more than one shift might be required. That could mean working part shifts, which may be inefficient or impractical;
- the operatives lose out and may resist different and longer working hours for the same pay; and
- people and management may be a constraint as they currently tend to avoid risks; this can change over time.

4.4.4 Method (process). Methods refer to the performed process and the particular requirements for performing them. Lean production plays a major role in increasing the productivity and product quality while reducing the waste and cost. Key factors include the following:

- the type of contract will influence behaviour;
- approach to risk, giving confidence to all concerned;
- programme planning, which can positively affect many of the above constraints through balanced planning; and
- picking the right team configuration specific for each type of job.

4.4.5 Information (measurements). Measurements or information refers to the data generated from the different processes that are used to evaluate quality:

- Loops will affect the process. However, the said loops affect tonnage but not necessarily utilisation.
- Most of the improvement made would also improve the loop process, in that more could be done on each shift.
- The design of the product will affect the process, i.e. deeper surfacing may require periods of curing between layers.
- Figure A8 shows the root cause analysis in the form of a fishbone diagram for better understanding and visualisation.

5. Simulation model design

The definition of the simulation scope is crucial for defining the analysis boundaries. Clearly defined scope of simulation system and boundaries could result in more useful simulation. The scope of simulation development in this study was limited to the activities involved from the start of road surfacing activity (i.e. from the time of road closure for surfacing purpose) until the road is open again. Programming of the project, the constraints of material deliveries or what goes on at asphalt plant/quarry level are beyond the scope of the presented simulation.

After defining the boundaries, it is important to identify the key assumptions about how the system being studied acts together with its defined external environment (Beaverstock *et al.*, 2014). The following assumptions were considered in building the simulation model. Preparation and logistic activities were included in the model, taken as fixed timings as measured on site, and are not part of the analysis. The simulated operation activities included planning, sweeping and pitch spraying, paving, rolling, white-lining and testing. Any sub-activities within each one of these activities were not considered. All the materials required in the process were assumed to be always available and delivered on time. Downtime of equipment was not included in the simulation. Also, the simulation was based on paving 45-mm thick surface course. Figure A9 shows the simulation model developed using the software called *FlexSim*. Figure A10 shows the 3D simulation of the equipment and process.

The research has focused on addressing the waste inherent in pavement laying process. Even though external variables could possibly influence the pavement process, those were ignored to allow for in-depth focus on the process under consideration. This has been acknowledged as one constraint of the analysis presented.

While modelling the random elements within the road surfacing process, it is important to replace time certain components with a probability distribution. Three randomly distributed components were used: asphalt inter-arrival delivery, asphalt truck position time and paving times. When analysing the system using simulation, times from these distributions can be "sampled" and used to recreate a typical cycle of the process. The simulation of multiple cycles can then provide attributes of a particular operative set-up, such as overall time and average planning or paving rates. To obtain a realistic simulation model, actual data from site operations was used. According to Smith (1998), the following steps are involved in modelling a simulation:

- gathering actual data;
- probability distribution selection;
- generation of variates (random samples) from these distributions;
- simulation of resurfacing operations; and
- experimental analysis of surfacing operations.

To determine the probability distributions used to model the resurfacing process, historical data collected over 115-night shifts over a six months' period was used. To select the suitable probability distribution, the historical data were analysed and tested against Anderson–Darling normality using a statistical distribution software application *Minitab 17*. As the paving process constitutes a major operation, other subsidiary processes such as planning were assumed to match the production rate of the paver. However, detailed analysis of the data indicated the average time for planning was 2.17 tonnes/minute and the average time for paving was 2.19 tonnes/minute (Figure A11).

The following calculations were done to have unified units for use in *FlexSim:* The process flow item is assumed to be equal to 1 tonne of asphalt. For paving, the average paving rate is 2.19 tonnes/min i.e. 131.4 tonnes/h, which means that 1 tonne requires 27.40 s to be paved.

Paving is a rehabilitation process and is not treated as a typical construction project. It has more resemblances with manufacturing when observed as a process. Using common distribution in manufacturing processes is prevalent. Further, the authors needed to find the average output of a typical paver to simulate various what-if scenarios. These calculations were done manually and then validated using the Anderson–Darling test. This is the reason common distribution was used here instead of beta, which is usually used in construction projects.

5.1 Simulation outputs and validation

With a small difference in values, the simulation outputs confirmed the need to improve the current state as the percentages of paver utilisation were considered to be low compared to the permissible work window of the shift. The paver was working only for 38 per cent of the time starting from road closure until the road was open again (Figure A12). These outputs and percentages provided a credible evidence of the waste inherent to the process of road surfacing. It can be concluded that the major waste in the process was in the form of "waiting" for the paver to start processing (waiting time). In the existing process, the aggregate is called and requested only when the planning process has started, which puts the paving process on hold for about 2 hours until the material is delivered even though the road has been prepared for laying of asphalt (i.e. the road is planed, swept and sprayed). There is an opportunity for process improvement, as presented by applying lean concepts, and eliminate the identified waste by shifting ahead the start time of the paver. To do so, the request of material delivery has to be done before the start of planning process. The processing duration of paver is relatively short considering the work window of the shift. Another opportunity for improvement is presented in extending the operation time of the paver, which means requesting material early and more planed, swept and sprayed surfaces.

Figure A13 shows the simulation model of the improved state. Key improvements involved ordering of material before the start of on-site activities. Because of increase in shift size and early commencement of pavement operations, the overall paver utilisation reached up to 67 per cent.

To validate a simulation model, two categories of data are required. First, there is need to collect robust and detailed data from the job site. Second, for validation purpose, empirical data on production rates and machine utilisation rates are required, to allow for a comparison with the model output. The output created by a DES simulation model consists of results mimicking the physical project for the model to be validated. Both categories of data came from various sources, including the company's sheets, reports and site observations. Also, some scenarios were simulated to validate the model, and they produced the following results:

5.1.1 Scenario No. 1: creating zones within the job site and increasing the number of planners and pavers. The first scenario assumed dividing the job site into two equal zones, Zones A & B, as shown in Figure A14. Each zone had its planners, one for each lane, while maintaining two lanes closed for resurfacing and two lanes open to public traffic. Both zones shared two pavers, five sweepers/pitch-sprayers and four rollers. In the same time, the scenario maintained the same work window. The key expected outcome was increased production in laid asphalt.

The simulation output is presented in Table III, with the total production rate increased up to two times (i.e. 276.9 tonnes/hour) the normal production rate. The simulation shows that the utilisation of pavers through the work window remains the same despite added machinery with an average utilisation rate of 65.3 per cent. As a result, an increment in the total production and production rate was expected, and the outcomes of the simulation met these expectations. Even though the production output increased, the added cost of extra machines should also be taken into account.

Table III.
Results of Scenario No. 1

Scenario 1: Using two pavers and closing two lanes together			
Paver total output	Paver Avg. output	Paver 1 utilisation	Paver 2 utilisation
1,892 tonnes	276.9 tonnes/h	65.3%	65.3%

5.1.2 Scenario No. 2: providing a 30-min break from 2:00-2:30 a.m. This scenario focused on measuring the impact on production rates in the case of a 30-minute worker break from 2:00 a.m. to 2:30 a.m. Single paver operations were assumed. A 30-min break resulted in a decrease in the total production and production rate. The break decreased the total asphalt laid to 865 tonnes in comparison with the previous scenario of 1,892 tonnes' output. The production rate was recorded as 126.6 tonnes per hour. The utilisation of the paver through the work window shrank by 5.6 per cent. Thus, a 30-min break could lead to significant delays in larger projects. As a result, staggered break times are suggested, in which each team takes its break in a manner that does not affect the flow of work (Table IV).

5.1.3 Scenario No. 3: forecasting the time required to carry out a certain job. The third scenario assumed limiting motorway closures to a 6-km stretch. Two lanes were closed at a time for public traffic and 45-mm thick asphalt was to be overlaid. Each closure interval (two lanes) required one 1 extra hour to complete resurfacing of the closed lanes. The extra hour was required during the paving operation. Thus, additional investigation of the paving operation is required to accelerate the operation and reduce the required time by 1 hour instead of adding 1 h to it. Finally, resurfacing of the entire closure area required an hour to be added or eliminated from each shift (Table V).

6. Discussion

Literature review indicated that while there is an uptake of lean concepts and tools within the manufacturing, process and construction industries, there are very few examples and limited use of value stream mapping and process simulation within road transportation context. There is a need for integrated approaches that allow for a comparison between the performances of such practices in the existing systems (Detty and Yingling, 2000). An integrated VSM-DES framework based on the literature review presented a systematic description of how future VSM can be validated before implementation to achieve success. McDonald *et al.* (2002) explained how the integration might be able to predict the outcomes of dynamic situations that VSM alone is not capable of addressing. Once the current state is mapped, the workflow splits into two paths where DES and VSM are conducted in parallel.

By implementing a similar framework in the highway sector, critical paths and value stream maps can be visualised, validated and amended with changes in factors. Simulation can be performed at a micro and a macro level in resurfacing operation. For instance, it can map a truck travelling from an asphalt quarry to the work site and experiment various situations when this truck is delayed or broken down. In the same way, an end-to-end process can be drawn of any similar activity e.g. earthworks, traffic management etc.

This study dealt with the complicity of adopting lean concepts and process simulation technology for driving changes in the construction industry. A systematic approach was

Table IV. Results of Scenario No. 2

Break from 2:00 to 2:30 a.m. Paver total output	Paver Avg. output	Paver utilisation
865 tonnes	126.6 tonnes/h	59.7%

Table V. Results of Scenario No. 3

Scenario 3: Closing two lanes at once Paver total output	Paver Avg. output	Paver 1 utilisation	Paver 2 utilisation
1,892 tonnes	276.9 tonnes/h	65.3%	65.3%

presented for the application of lean construction concepts and tools to computer simulation models for increasing road surfacing productivity. These improvements were tangible, i.e. the waste (waiting time) as well as other non-value-adding activities were noticeably eliminated or reduced. The hourly production rate, resource (paver) utilisation and project duration were improved dramatically as a result of implementing lean concepts and tools.

In terms of the simulation, the numbers and rates shown in the model's output confirmed the validity of the models, thus opening up opportunities for producing a template model that includes deeper and more detailed factors that could affect the entire process, such as distance between job site and asphalt plant, failure of machines, delays caused by work accidents, severe weather conditions and delivered material failing under initial inspection. Further site observations and a detailed collection of data are required to build a further realistic model.

Material delivery time is also linked to the working style of the team on site. One of the major causes of delay in everyday work was that after the start of traffic management started and arrival of the team on site, material was called in as the last step. It then took time for the material to arrive on site. In the improved process shown in Figure A5, material was called in before the traffic management was started, giving enough time for it to arrive.

It was noticed during data collection and analysis that the road surfacing contractor only used the paving machine for 2 h of the 8-h work window allowed. This decreased the efficiency of the paver to 25 per cent which was a pure waste of resources. However, after improving the process, the efficiency reached up to 75 per cent. Road users are one of the most important stakeholders that will benefit from the positive implications of this study. Private resurfacing companies and transport departments can optimise their overall process and style of working by comparing their end-to-end processes and work plans with the ones mentioned in this paper. It will boost the productivity of equipment like planners and pavers and other machines used for resurfacing operations.

7. Conclusion

The purpose of this study was to investigate the relationship between DES and VSM and then apply it in highway operations to increase production rates and minimise road closures. Different scenarios were considered in the simulation to optimise the process. The best practice can be chosen after validating it through focus group discussions, workshops, etc. The case study results showed that just changing the working style can give huge benefits.

Although resurfacing and repairing of roads are inevitable, they can be optimised to an extent that general public is not disturbed by such operations. It is a well-accepted fact that stakeholders such as "motorists" are usually displeased about the continuous roadworks. There is scope for improvement in this regard by drawing upon the implications of "creation of zones" discussed in Scenario No. 1. (Figure A14).

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Further reading

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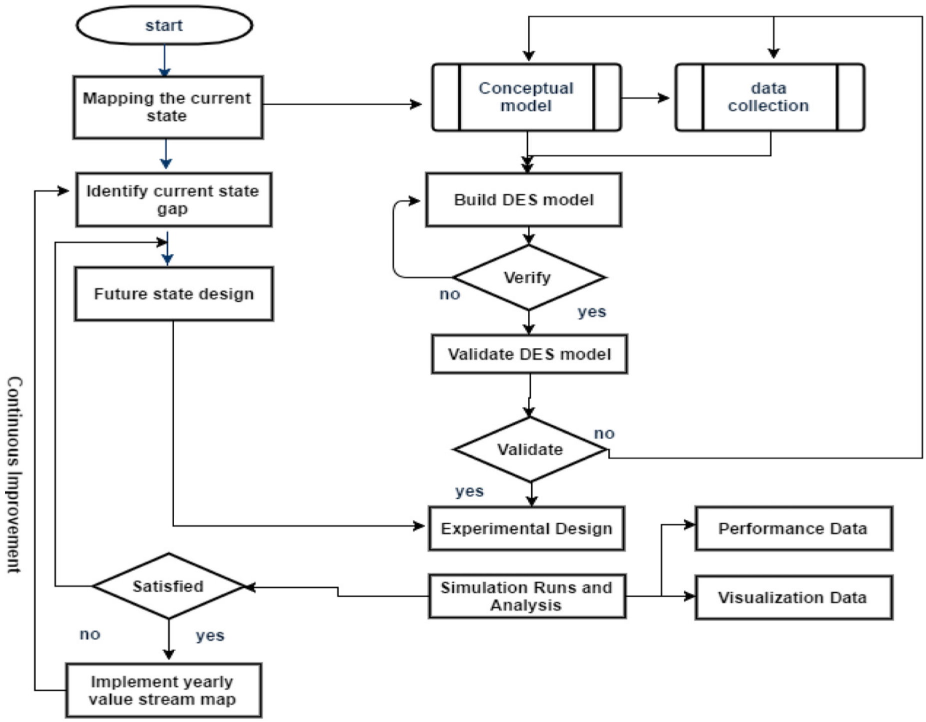
Appendix



Source: McDonald *et al*. (2002)

Figure A1.
DES-VSM integrated framework

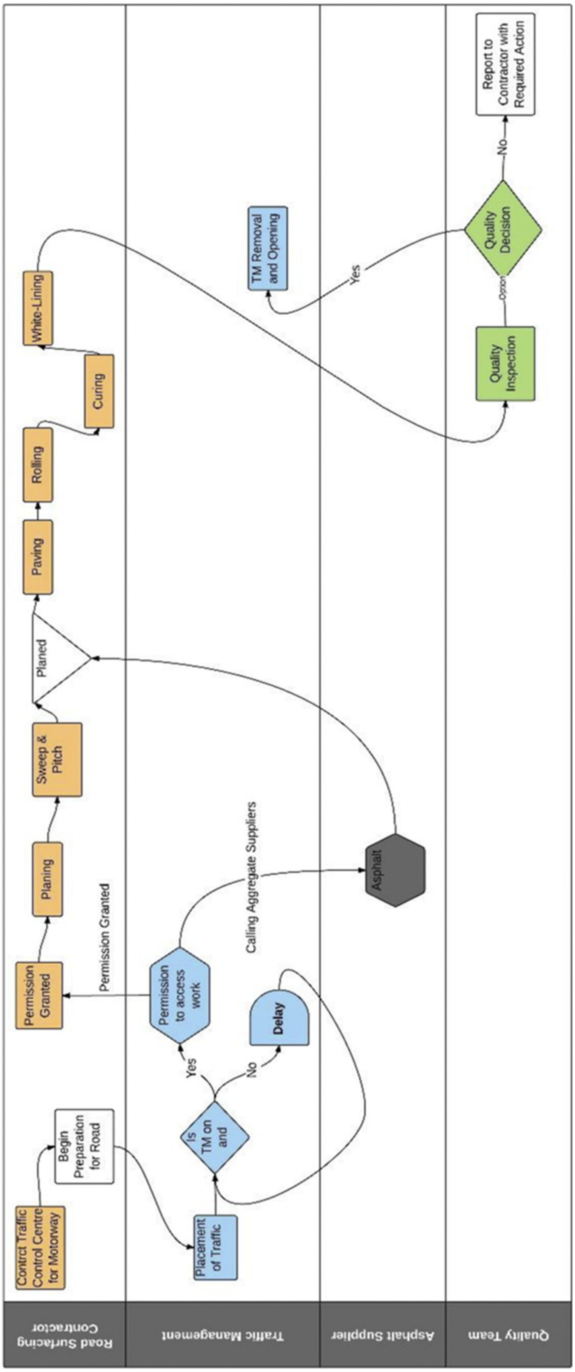


Figure A2.
As-is road pavement surfacing

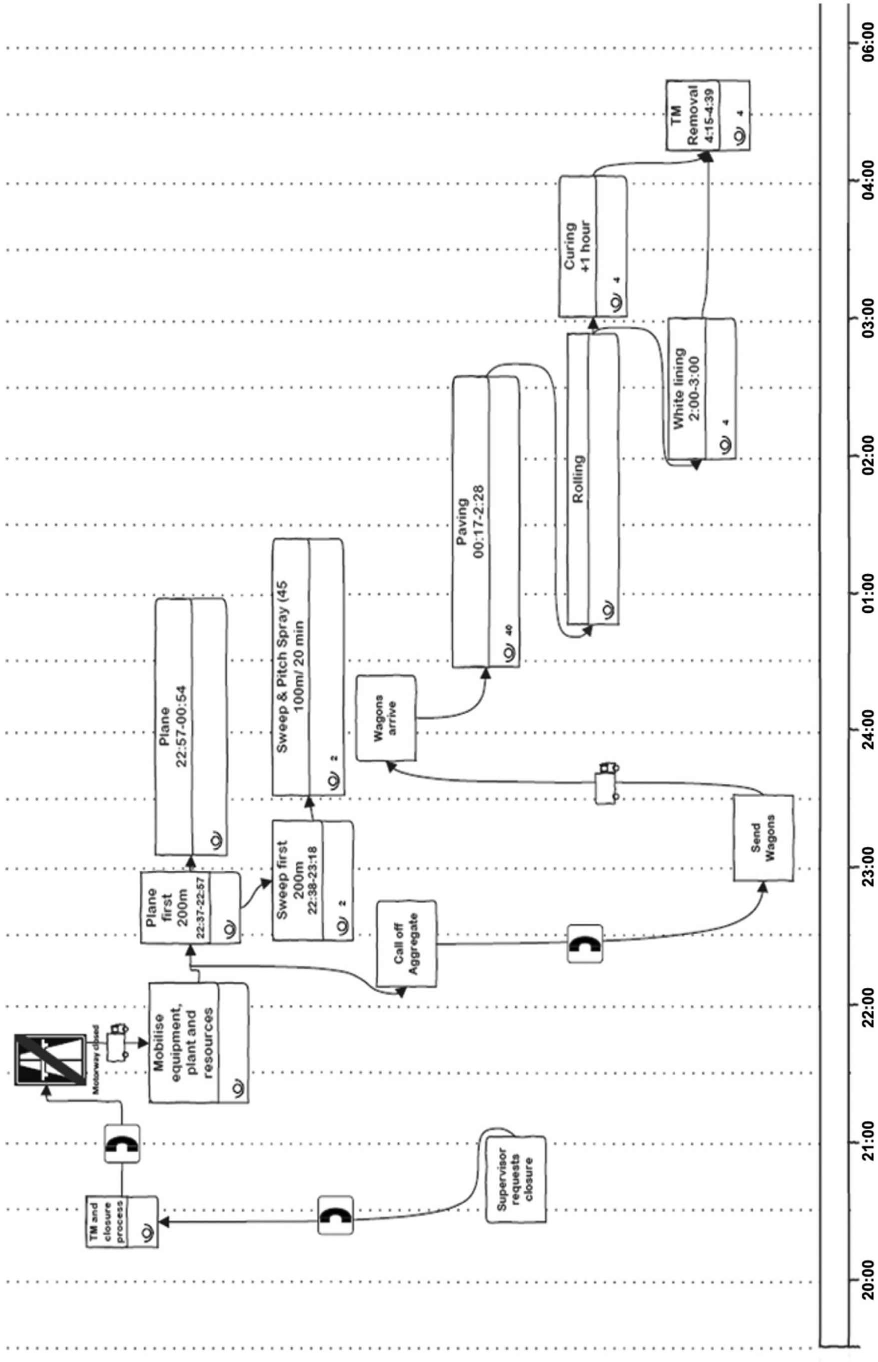
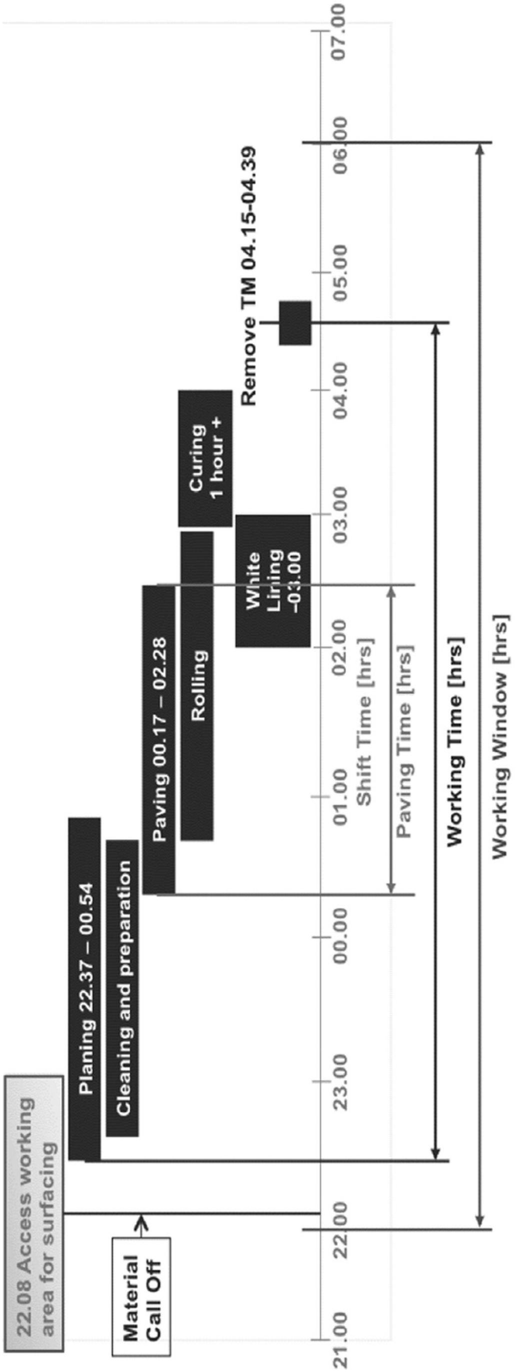
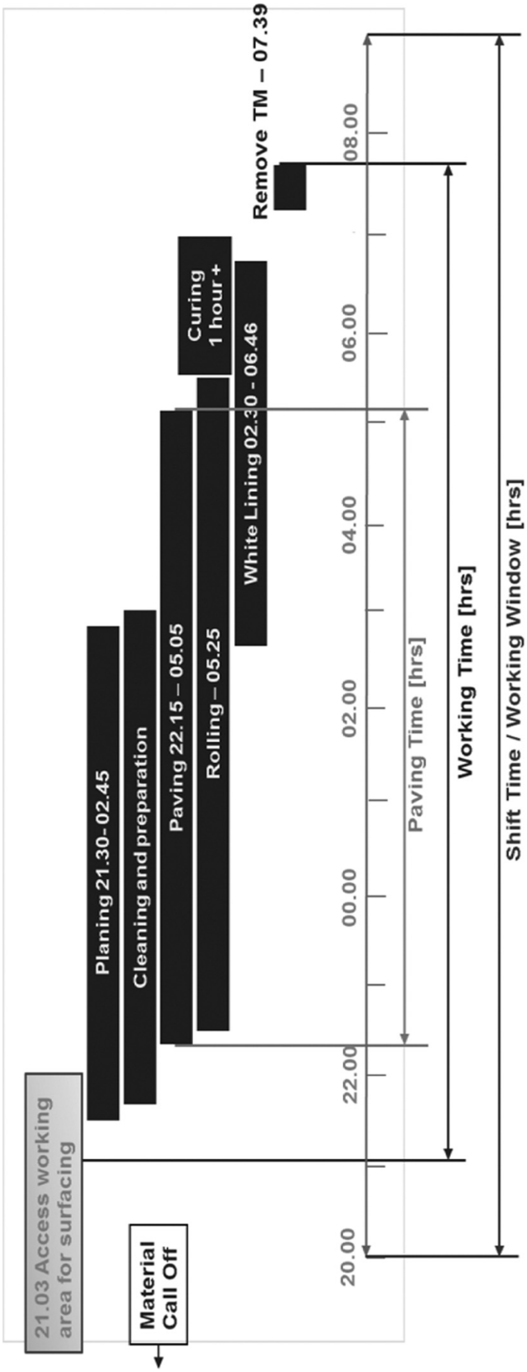


Figure A3.
VSM of as-is road surfacing process operations



Source: Moore (2015)

Figure A4.
Road resurfacing operation, "as-is process"



Source: Moore (2015)

Figure A5.
Road resurfacing operation, improved process

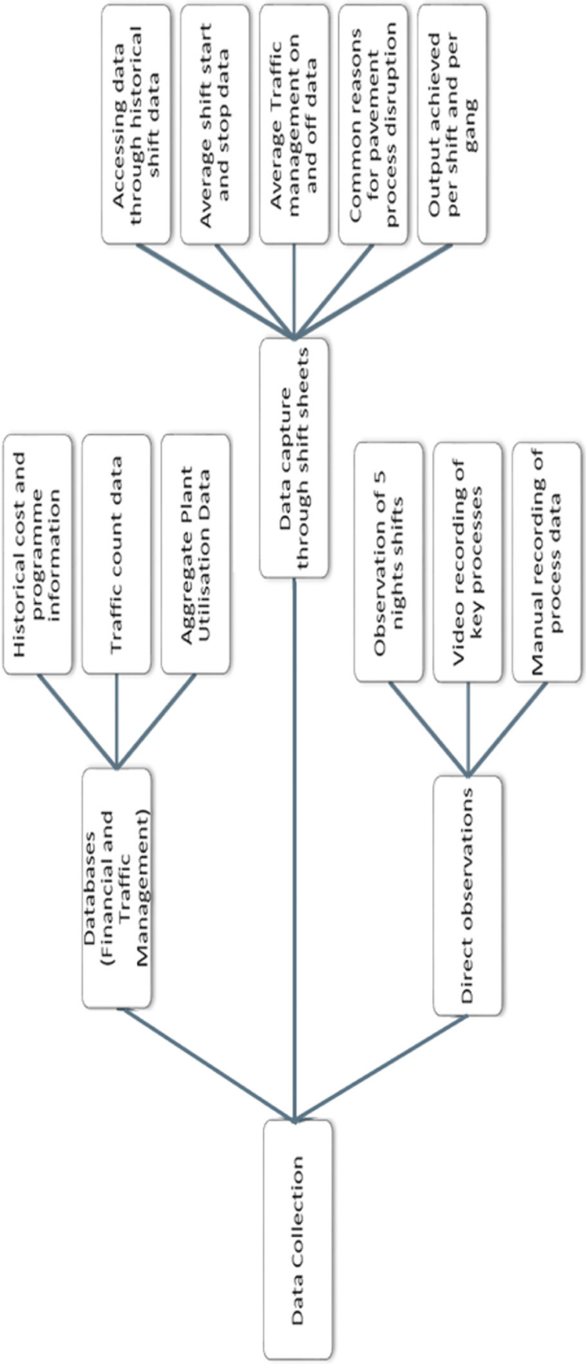


Figure A6.
Data collection methods

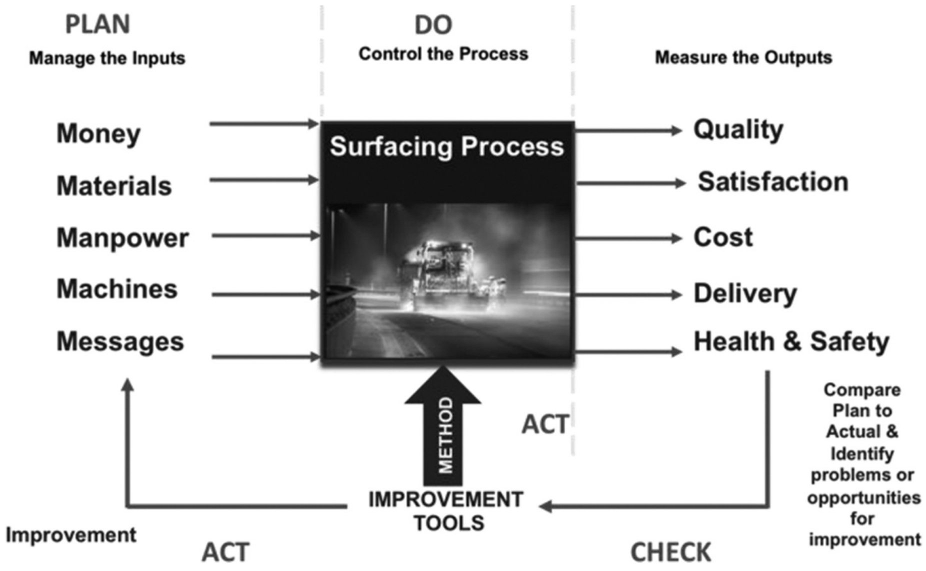


Figure A7.
Road surfacing process model

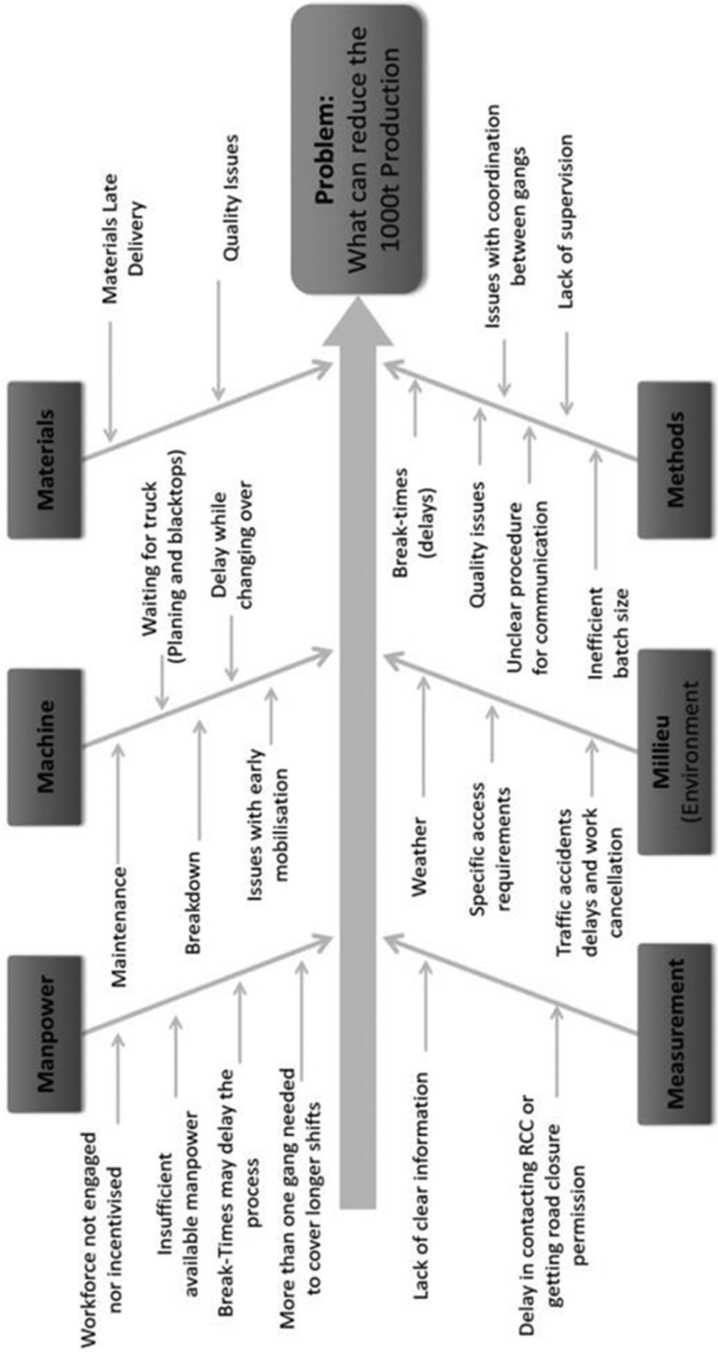


Figure A8.
Root cause analysis

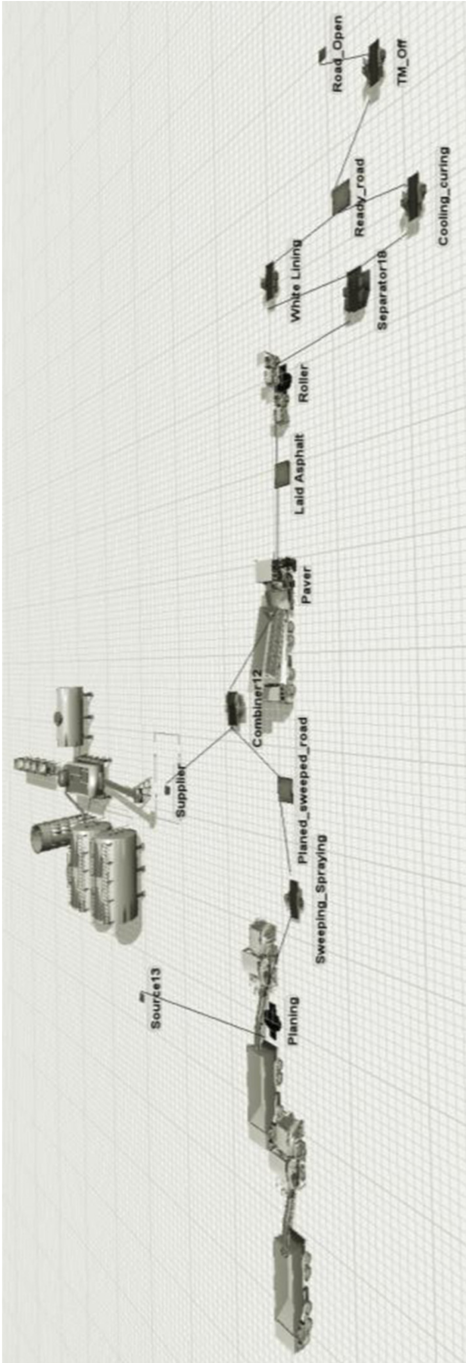


Figure A9.
FlexSim model representation of "as-is" state of road resurfacing (software used FlexSim)

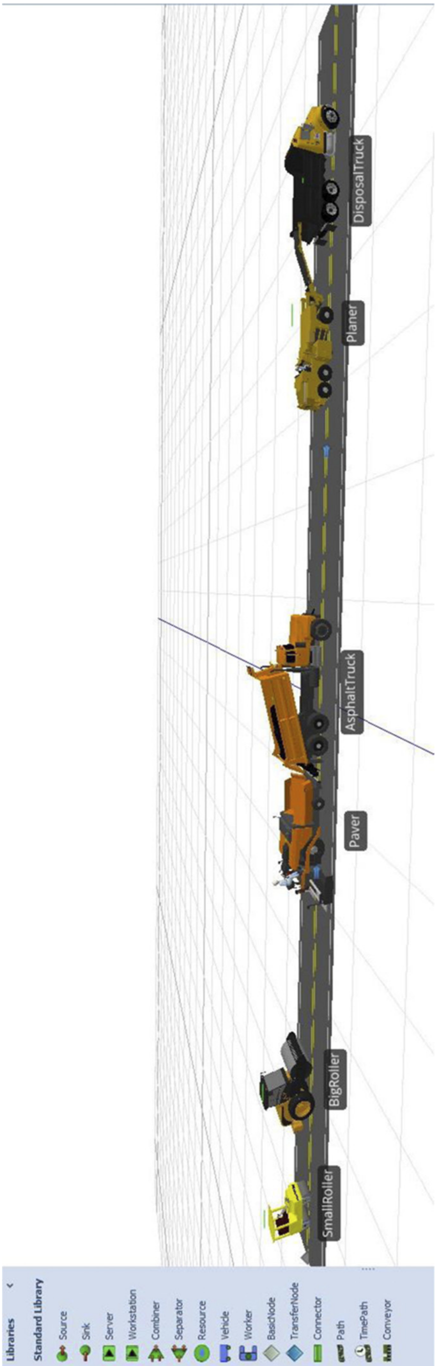


Figure A10.
3D presentation of asphalt machinery (software used: Simio)

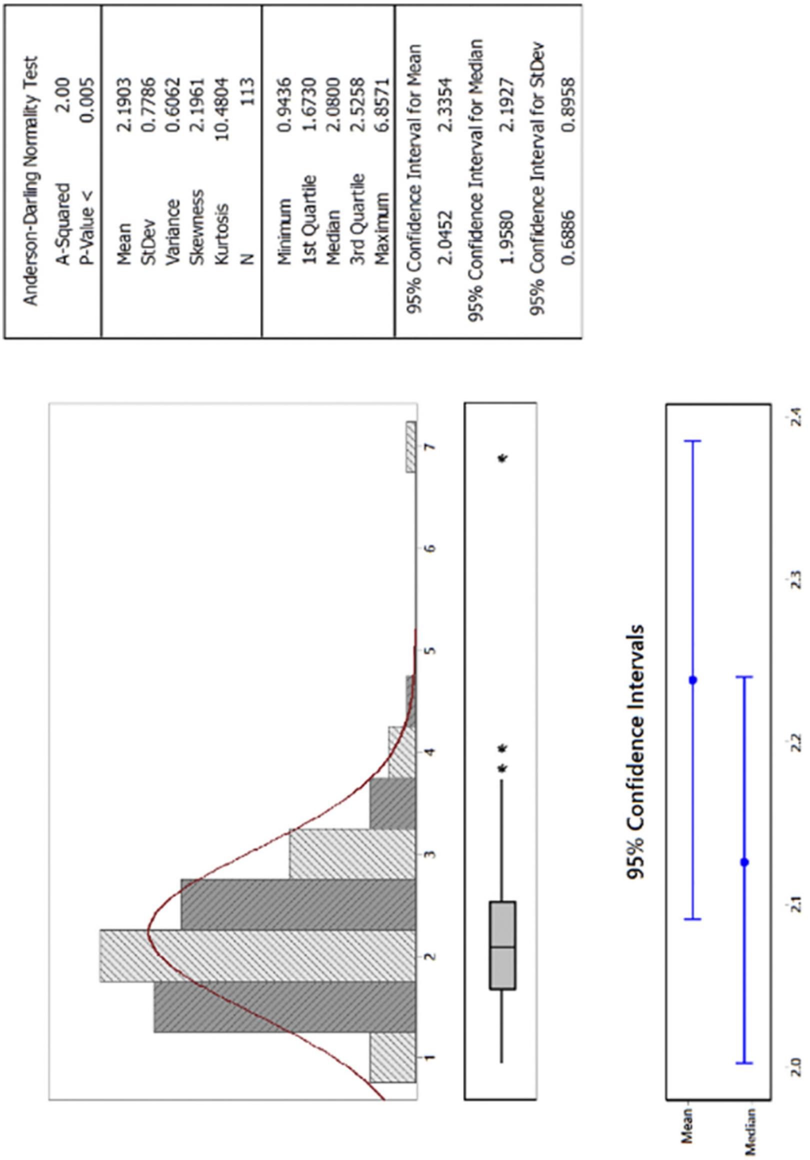


Figure A11.
Summary of paving rates (tonnes/min)

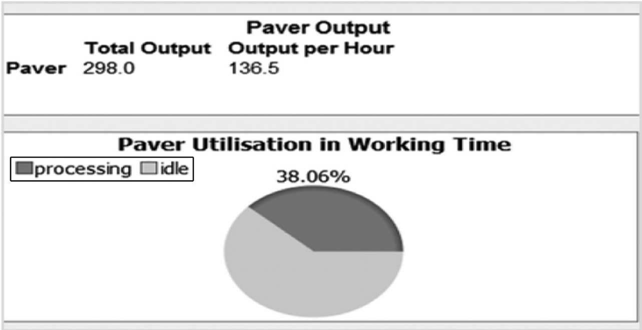


Figure A12.
Discrete event simulation output of the as-is process (*FlexSim*)

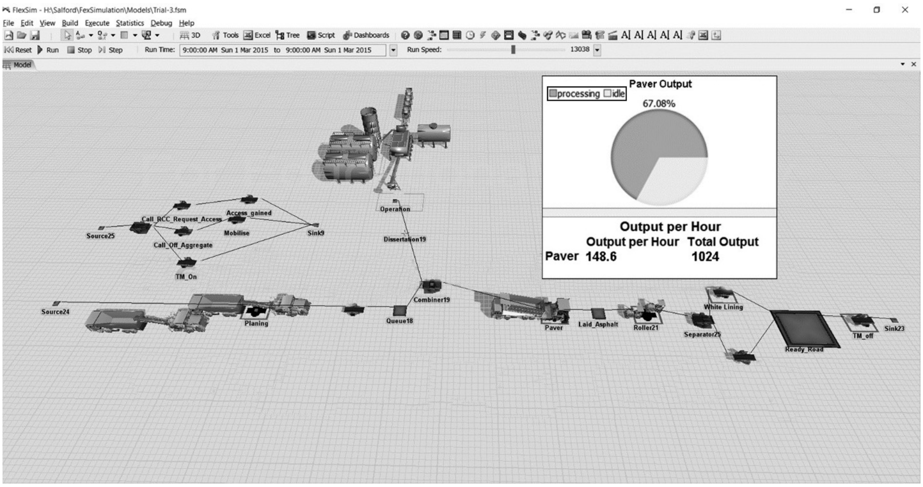


Figure A13.
Future state after eliminating the “waiting time” waste from the process

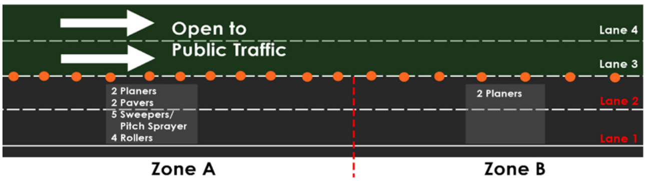


Figure A14.
Scenario No.1 zoning plan

Corresponding author
Rana Muhammad Qasim can be contacted at: m.qasim1@edu.salford.ac.uk