The Asphalt Construction Site of the Future – a Dutch perspective

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Abstract— **This paper brings together challenges facing asphalt construction in the Netherlands and the vision for a Construction Site of the Future given ever-changing requirements of the road construction industry. Drawing on the experiences of more than 40 case studies monitored over a period of eight years, this paper highlights a few key issues relating to process improvement and how it can be addressed using current construction informatics. The vision is firstly communicated to professionals using a scenario for the asphalt Construction Site of the Future. The scenario is intended to highlight the potential benefits of integrating new sensor technologies and informatics into the rather complex asphalt construction process. Current practical challenges are then addressed including the development and integration of real-time information systems to support the process in the context of operational, tactical and strategic decision-making. We highlight the developmental implications for the construction industry should the vision for the future be adopted, the potential benefits of implementing new sensor technologies and informatics, the effects on human resources, and the potential impact on knowledge management initiatives. Finally, we position the important roles of public clients and contractors to successfully address challenges of variability in the asphalt construction process.**

Keywords—asphalt; construction; process control; quality control; quality assurance

I. Introduction

All asphalt professionals aspire to design and construct asphalt roads that last for its intended design life. Roads, that after construction, perform as intended. From client to designer to constructor, the goal is the same, that of ensuring that the final product meets all of the functional and mechanistic requirements carefully thought through during feasibility and design and constructed with care and due diligence. The client needs nothing more than to look after the interests of the tax payer, ensure that the final product is value for money and that it lasts for its intended life without the need for early maintenance interventions. The designer attempts to meet this goal by addressing the functional and mechanistic requirements with due diligence to ensure that the needs of the client are met. The contractor, in turn, tries to meet the needs of the client and designer by carefully following method statements to construct an asphalt layer that if carefully built, will be durable and last for its intended design life. However, we know the reality is often a little different. Clients are often faced with roads that fail prematurely, often do not get value for money and quite frankly are left carrying the can so to speak after guarantee periods have elapsed.

Yet, we know there are roads that have lasted for their design life, that meet the intended functional requirements and design specifications and ultimately, bring joy to all those involved in its creation. Clients, designers and contractors are often lauded for their contributions to society through innovative engineering design competitions [1]. Road construction's importance to society is emphasized with industrialized countries typically spending just over 1.0 percent of GDP on the road sector [2]. Those with road funds typically spend over 1.5 percent of GDP. The European Union's construction sector was made up of 3.3 million enterprises in 2010, employing 13.4 million persons and generating € 496.1 billion of value added [3]. The conclusion drawn is that the construction industry is here to stay since it forms an integral and vital part of most economies.

Given all the positives related to road construction, the question then arises as to why issues relating to premature failure and a perceived lack of value for money amongst others, are still regularly raised. Eight years of research carried out by the Asphalt Paving Research and Innovation (ASPARi), a purposeful mix of researchers and contractors in the Netherlands provides some interesting insights. Whilst there is immense pride for road construction and role players undertake their tasks with the utmost care, this research has shown that for asphalt construction, many tasks are still being carried out without measuring important process parameters, work is often undertaken based on tradition and custom, learning takes place implicitly and despite a plethora of available new technologies appearing on the market, operators tend to ignore the "bells and whistles" on machines and undertake tasks using the tried and trusted "experienced-based" operational strategies [4]. The result is that there is considerable variability in the constructed product [5].

The issues described above have typically embraced a number of challenges for researchers and all role players involved in asphalt construction. We therefore dare to dream of being able to adequately deal with these challenges. Prominent researchers and asphalt experts have in the past dared the construction industry to think differently [6] and suggested that a different approach to asphalt quality be taken given the magnitude of variability in the quality of highway construction, and resulting concerns about the need for improved specifications [7].

II. ASPHALT CONSTRUCTION SITE OF THE FUTURE

It is in this context that we dare to describe a future scenario and illustrate how current sensor technologies and informatics can support achieving the improvements sought after by the asphalt industry. Unlike earlier research efforts depicting construction sites of the future [8, 9], the scenario does not assume that the traditional roles and responsibilities of construction staff remain the same. The actors in the script are shown in Table 1 below. Please note that the vision has purposefully been written in a rather lengthy narrative to give readers an appreciation of the somewhat complex asphalt construction process and how this may unfold in the future. Since it is illustrative, the reader may continue to Part III of the paper.

TABLE I. ROLE PLAYERS

Name	Job Title	Company
Pieter	Site Manager	Contractor
Jan	Work Planner	Contractor
Erika	Pavement Engineer	Contractor
Tom	Paver Operator	Contractor
Clive	Roller Operator	Contractor
Fred	Screed Operator	Contractor
Anna	Roller Operator	Contractor
Sander	Ancillary Workman	Contractor
Shadrack	IT programmer	Contractor
Don	Milling supervisor	Subcontractor
Ali	Works inspector	Client

A. The future asphalt construction site scenario

It is a typical Friday afternoon in the Spring time. Relatively warm with little wind on site. The rain forecasted for earlier in the day has not materialized. Pieter, the Site Manager has been on site since 06:00 with his team, supervising the paving of a standard asphalt base layer. The work has proceeded smoothly thus far leading him to cast a wry but rather weary smile. The Client's Chief Engineer has not been on his case at all, neither has the Works Inspector casting an eye on a large screen mounted in the asphalt team's mobile site cabin. He has not been in touch with the plant at all during the day or with his company's offices to complain. "It is turning out to be a good day" thinks Pieter and walks to the mobile site cabin to monitor the work and review the next few weeks' work.

He starts up his tablet, links it to the wall mounted monitor in the mobile cabin and views the location map of all projects lined up for the team. While scrutinizing the map, he download details of the locations, mix designs, quantities, road widths and equipment requirements to his entire team's SmartPhones. It will form the basis of a short planning discussion in the cabin before the staff leave the site at the end of the day. It may just be another smooth week lined up for the gang.

His thoughts are suddenly interrupted by an alert for a video call from Head Office. He calmly takes the call and Jan, a Works Planner explains that the company has taken on some emergency repairs to a freeway in the area. It appears that freeze-thaw cycles during the winter have caused the porous asphalt surfacing layer to pop. 2km of dual carriageway has to be repaired outside of the peak hours, meaning night work for the construction team. "As long as everything is properly organised, there should be no problems with this rental agreement job and no risks of fines hanging over the team's head" he thinks. Jan shares the high resolution video images captured by the company's IT guys a week ago. The videos captured in off-peak traffic, clearly show a surface in distress and in need of urgent repair. Pieter asks whether the videos have been converted into strip maps to show the different types of distress. He is concerned that it may be more than the surfacing layer that needs repairing. A puzzled Jan suggests that Erika, the head of Pavement Engineering, joins the video call and alerts her. Erika explains that the client only wants the surfacing layer repaired to ensure that the freeway remains open to traffic. She has the go ahead from the company's tender and legal departments and calls up the necessary proof from the document repository to show that the scope of work has been approved. Pieter sends an alert to his team to warn them of the change of plans for the coming Monday and passes on the location via a group app on his SmartPhone.

It is Monday afternoon at 17:00. Pieter calls his entire team together for the customary briefing in the mobile cabin whilst the traffic accommodation team gets to work at 18:00 and milling operations start soon thereafter. He alerts Jan and Erika who are at their respective offices at the start of the meeting. All eyes are focused on the monitor where Erika explains the characteristics of the mix to be used. The client has agreed to use a standard porous asphalt mix design previously approved for a similar project carried out by another asphalt team, almost at the same time the year before. Fred stresses that it has been a long time since they worked with that specific mix and enquires whether they have the mix and construction details for the year before. Erika logs into the database and shares the lab tests carried out before and after construction. The pre-construction tests showed that the mix appeared to perform better when compacted between 140°C and 100°C and with between 10 and 12 roller passes. She highlights a few issues. There is a risk of permanent deformation occurring if compaction were to start at the higher temperature ranges. Also, post-construction tests showed that although there were no density failures on the road, micro-cracks appeared on the surface soon after construction. Erika shows the group the density progression charts for the project which shows that the final compaction phase consistently continued to mix temperatures as low as 60°C, a definite cause for concern and something the team should pay attention to. Clive jokingly asks whether the roller operators were wearing their head sets and whether the compaction zone monitors were activated. Sander asks whether the asphalt team was given the results of the pre-construction tests and advised of the desired compaction window? An eerie quiet descends as Erika avoids the issue. Pieter breaks the silence stressing the need for communication protocols to be observed during all phases of the work.

Paver operator Tom turns his attention to Jan and asks for details regarding the logistics arrangements between plant and site. Jan explains that as usual, one of the lanes on the freeway must be kept open to traffic. His calculations based on historical data for the area, shows that the trucks may get stuck in traffic in the first hour of paving. An alternative, longer route has been chosen for the first hour to ensure that there is a continuous supply of asphalt. His recently acquired simulator also confirms the number of trucks to be used in the cycle to be sufficient to guarantee a continuous supply if the paver were to move at a constant speed of 4m/min. Having exhausted all logistical issues from a prepared checklist on his tablet, Pieter thanks Erika and Jan for their input, waves them goodbye and turns his attention to his team. The next activity is to line up paving and compaction operations. Attention is once again focused on the monitor as he takes over the company's software from Erika and Jan and starts up the Construction Site Suite. The cabin is a hive of activity as every member of the team logs into the system on their tablets. Sander, the ancillary workman in charge of all handwork, jokes that his has fallen so many times, been trodden on repeatedly by his toddler and still manages to keep going. Even the constant heat around the paver does no harm to the rubber insulated workhorse. An input screen appears on all tablets. Tom inputs the paver speed based on Jan's calculations. Sander, recently tasked with monitoring weather conditions before, during and after the project, enters the wind speed, air temperature, humidity and clear skies forecasted for the evening. Responding to grumbles, he assures the team he is using the forecast from the mutually agreed website. Pieter then focuses on the existing surface which is to be milled off between 19:00 and 20:00. He comments that there is nothing out of the ordinary to note and that the team should be able to start paving as scheduled. This is confirmed with a check of Erika's inputs. He then checks the Logistics tab on the software which confirms that the first truck is scheduled to arrive on site as scheduled at 20:30. Even though he is not new to the software, he does a quick calculation to check that the number of trucks in the cycle are indeed correct. Using a simple fleet demand spreadsheet he developed himself, he inputs the distance between plant and site, average truck speed, average waiting and loading times, average truck capacity, the tonnage for the night and lastly, the hours available for his team to complete the repair job. He smiles as his calculation and that of the software more or less match. Jan's alternative route for the first hour shows that an extra truck is needed to ensure the paver having a continuous supply. Sander amusingly suggests that Pieter deal with his "trust" issues. Pieter reminds the team that it is not so long ago that all were sceptical of the software until they were gradually involved in its development and had taken responsibility for the process.

Fred, the screed operator, interrupts the nostalgia and raises his concern regarding the last "mill and fill" project. The team was hauled over the coals for ordering an additional 20 tonnes of asphalt to complete the job. Although not being able to confirm it since the milling sensors were not as yet linked to the system, he suspects that the subcontractor's sensors were not fully operational at the time and that no milling data was provided post-construction. Pieter checks the database, confirms that no upload took place and immediately notes the urgent "link" suggestion in the electronic repository for Shadrack, the IT guy, to deal with it in the morning. It is also automatically loaded as an agenda item for the weekly management video conference. With a different subcontractor being used on this project, Pieter video calls milling supervisor Don and enquires whether his sensors are operational on the milling machine that has just commenced work. Don confirms this and emails a screen plot of the real-time milling depths appearing on his tablet.

With all inputs checked and agreed, the team moves onto planning the compaction phase. Clive takes over the software and with all input boxes checked, recalls the mix specification screen Erika discussed earlier. He points out that no modified binder is being used and workability tests show that the mix should be quite easy to work with. However, a wind speed of around 10km/hr is forecast for the evening which may result in about 20% less compaction time. A quick revision of Erika's input data and the theoretical cooling curve appears on the screen. With a lift thickness of 50mm, the window for compaction before the mix cools off to approximately 100°C is a mere 20 minutes. Anna, fresh out of roller operator training, asks whether two rollers are enough for the job given the lane width. Clive, the more experienced operator responds that having received the alert for this project, he used the online compaction simulator tool over the weekend to check his roller patterns and trajectory lengths for a similar project with similar lane widths and that two rollers should be sufficient for undertaking breakdown and final compaction tasks. Pieter mentions that he would keep his eye on them working in Erika's instructed "green compaction zones" given the reduction in available compaction time and will alert them if necessary. He also sends an alert to Shadrack for Anna's training and access to the online simulator. Having checked all the boxes, Pieter wishes the team well and they move to their respective machines for that part of customary checking procedure.

It is 20:00 and all milling, cleaning and tacking operations are finished. Tom adjusts the paver's position at the start of Lane 1. He inserts his tablet into the docking station and, checks that the GPS receiver and the laser line scanner are both working. He enters the agreed paver speed and checks the rest of the settings. He presses the Logistics button on his tablet and it shows the exact locations of the trucks on the way to the site. The first truck will indeed arrive very close to the scheduled 20:30 starting time. Fred adjusts the screed settings after having seen the milling depths in a screen plot sent to his tablet and notes the slight change in depth at Km 3200. "Damn good milling subcontractor. Wish I could work with him every day" he thinks to himself and proceeds to start the screed heating. Sander checks his tablet linked to the team's portable weather station mounted on the mobile cabin. No significant change in the wind forecast and therefore nothing to report as yet. Clive and Anna are both on the ready having checked their rollers, inserted their tablets into docking stations, undertaken the necessary GPS checks by producing phantom screen plots on a section of road outside of the main work zone. Each sends an alert to Pieter's tablet that they are ready for work to commence. Pieter in the meantime, takes 5 minutes to set up the Cooling Curve Calibration Unit (CCCU) at the roadside. The unit's robotic arm will automatically place active temperature, pressure and moisture sensors into the asphalt layer where they will remain until the first scheduled maintenance. Having satisfied himself that the wireless connections to the paver and rollers are working properly, he makes his way to the mobile cabin. Ali, an experienced Works Inspector, is already settled in the cabin where he will jointly follow process control indicators. Pieter checks in with each team member to ensure that they are all using the headsets as per the agreed communication protocol.

The first insulated truck arrives on site and gently reverses into position in front of the paver. Tom checks that the number plate matches the first one shown on his Logistics screen, a check that it is the correct mix being delivered to the site. He switches to split screen mode so that the Logistics and the Temperature Contour Plots (TCP) are both shown. A single hoot and the truck driver starts dumping the mix into the hopper. Tom is mindful of the effect of cold starts and waits till the hopper is full before moving. The line scanner measuring directly behind the paver screed, shows the mix to have an average temperature of 155°C after a few minutes.

Other than being able to adjust the screed settings on his tablet, Fred is also able to follow the TCP in split screen mode. He informs the roller operators of the initial surface temperature and gives them the "waiting" call. The paver passes the CCCU and both roller operators instantly see the "RED no-go" zone appearing on their tablets. The wait seems like an eternity but Clive is mindful of the agreed roller strategy exhaustively tested and simulated in the laboratory. Just as the mix temperature drops to 140°C, he sees the onscreen alert and the "GREEN go" zone appearing on the tablet. A large enough work zone opens and he starts with breakdown rolling. He then switches to spilt screen mode so he can follow his own roller passes and coverage on the Compaction Contour Plot (CCP) at the same time. Anna soon follows, attentive to what her more experienced partner has repeatedly mentioned: "Stay in the GREEN temperature zone, concentrate on getting to the agreed compaction passes and we should be ok. The works inspector will be pleased with an in-control compaction process ".

It's 3 hours into the construction process. In the cabin, Pieter and Ali are still focused on monitoring the visualizations, process control indicators and other charts to check whether the process remains in control, wary that any chance causes could disturb the process. They have been in this game long enough to know that anything can happen. A plant breakdown, trucks getting stuck because of a road accident and the flaps not working on the insulated trucks are a few things that can go wrong. Luckily, they can react and possibly mitigate the cause almost immediately with little disturbance to the smooth running of the process. Pieter smiles while sipping his coffee and remarks "Remember those days when we had to fill in all those forms and the nonsensical as-built info? Ali my friend, nowadays all the data goes into the cloud, I press one button and you get the necessary georefenced data sent to your PC. We have come a long way my friend, a long way." Ali nods appreciatively looking forward to the post-project discussion with his manager.

III. Construction Informatics and the Future Site

The above vision highlights several challenges for asphalt design and construction. Most are of an operational nature and have to be addressed in "real-time" to have a positive effect on the final product. However, the move towards real-time process control brings along a set of challenges which include dealing with large data sets, processing continuous data streams on the fly and the integration of contextual data such as weather conditions and asphalt mix temperature when delivered to the construction site. Other than the listed challenges, there are also two pertinent issues to consider: (a) the current high cost of GPS sensors, laser line scanners, infrared cameras and other active and passive sensors being used to monitor the construction process, and (b) the rather invasive and labour-intensive nature of current data collection processes on construction sites.

This leads to a few questions: What should the system look like? Given current levels of technology, can such a system deal with the challenges mentioned above? It appears that developing an integrated real-time support system that will support the entire asphalt construction chain achieve a more consistent final product is complex. The question of how to best connect sensors, process the collected data, provide appropriate data visuals to sometimes distantly located operators and site managers in real-time and at the same time inform strategic decision-makers within companies is indeed complex. Even though a number of ways to collect sensor readings on construction sites were introduced over the past two decades [10-17] and many of these have been developed into industrial applications for asphalt construction machinery, few of the previous approaches focused on collecting and processing sensor readings in different levels of detail to support operational, tactical and strategic decision-making.

To address this gap, we propose a generic framework shown in Fig. 1 that enables distributed data collection and management whilst acknowledging the different levels of decision-making required on and off site [18]. The framework proposes to store sensor readings at different locations in different levels of detail. The proposed approach relies on several databases which means that the framework will benefit from the fact that the sensor readings are stored in different locations with different levels of detail. Put simply, the readings obtained with a high update rate are stored at the time of data collection. Then, the update rate of the sensor readings to support real-time visualizations is reduced to a level of detail that will inform the ongoing site processes. The reduced level of detail enables a reduction of the throughput requirements even if the bandwidth is low. The server can then provide very close to real-time information to several operators. In terms of decision-making, the highly precise readings are collected for permanent record purposes and analysis (strategic), the reduced detail in the form of visualizations for on-site personnel (operational) and external users can communicate with the system at a tactical decision-making level.

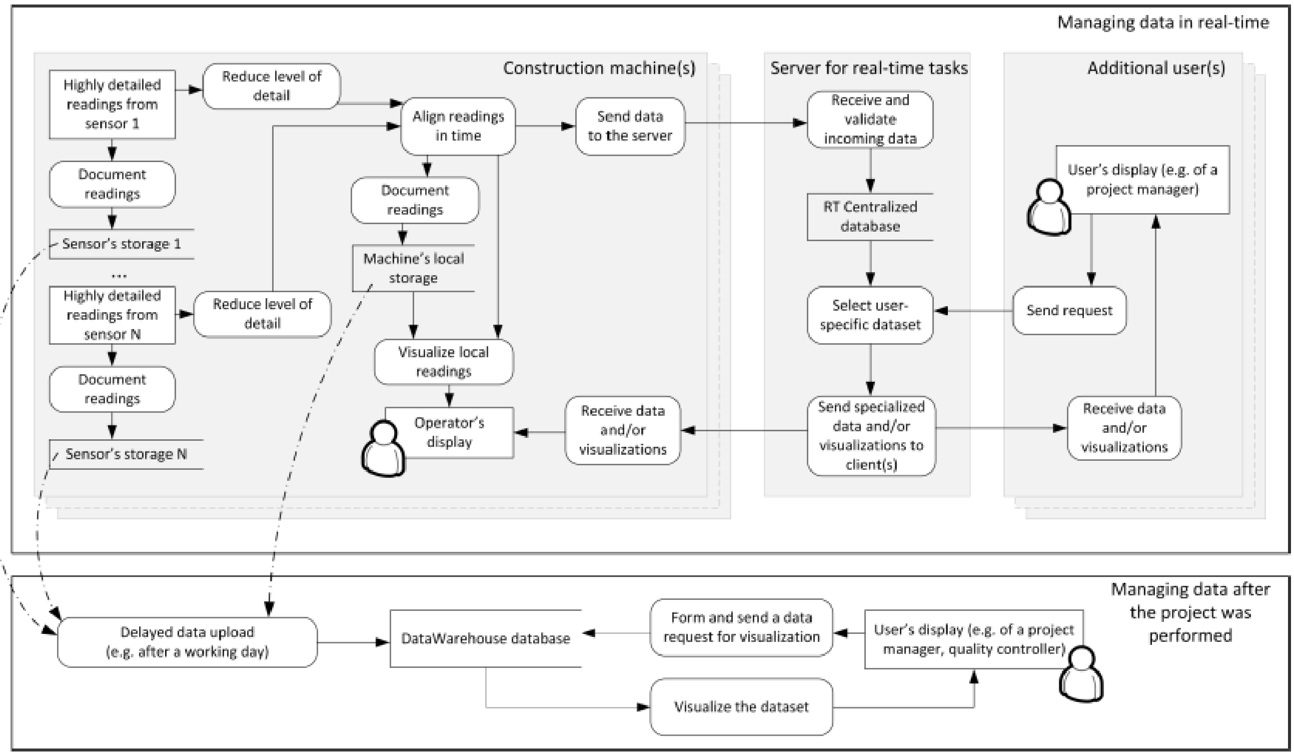

Fig. 1 - Proposed distributed data collection and management framework [18]

Also, to adequately process sensor readings the information systems should comply with two requirements: (1) support data transmission from a number of sensors to multiple clients, and (2) support real-time computations. The question then is how can we fulfil these requirements when the amount of sensors or users is continually increasing? The answer may lie in the current trend in computer science – cloud computing. Cloud computing allows (us) to utilize multiple servers connected via a network as if they were one processing unit. Such a cloud as is shown in Fig. 2, shares resources, processing power and is accessible on-demand from any location. Therefore, a central processing unit, connected via a network to all sensors and final users, can be employed as a core of the sensor-based infrastructure. By using cloud computing it becomes possible to receive readings from de-centralized sensors and immediately process them at specialized processing units. Then, the visualization is to be immediately delivered to distant users. The flexibility of cloud computing can be considered as the asset of the user-oriented information systems. In this way, the information system can benefit from the following advantages:

- Firstly, origins of information are not limited to a particular construction site. Users have access to the processed data independent of their geographic location as the communication lines exist there. Any kind of data transfer would work, such as broadband or 4G/GPRS connections. In fact, only a reliable connection to the Internet is required.

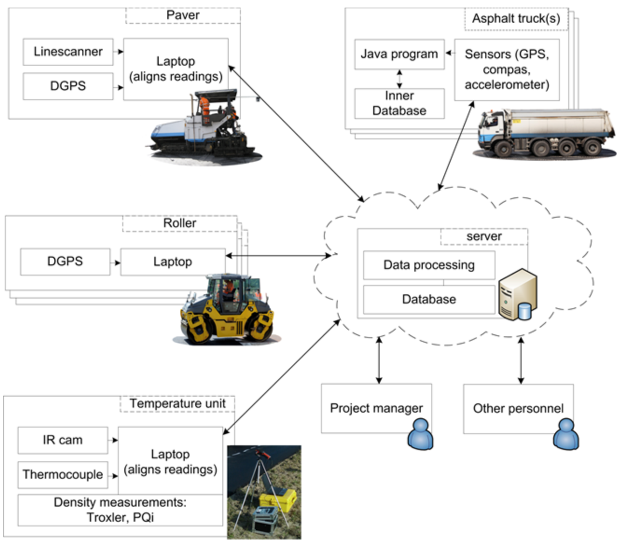

Fig. 2 – Proposed cloud scheme for collecting sensor readings [18]

- Second, there is no limitation on the number of sensors. For example, a large-scale construction project can utilize many sensors or, the same infrastructure can be used to control multiple projects at the same time.

- Finally, all calculations can be done within the computation centre, thus reducing the need for IT support on site.

IV. Key developmental themes arising from the vision

The Asphalt Construction Site of the Future scenario and the proposed informatics framework typically embraces a number of research challenges aptly described by [9] as being of a technological and managerial nature, together with issues of application and implementation, and relationships to construction process and product performance. The undertaken research approach [19] combined with recent rapid developments in sensors (GPS, RFID) and related IT systems for construction, makes it possible to construct this scenario of the future to which ongoing research and other developmental efforts may relate. The scenario contains several themes of how further developments in sensor technology and informatics may enable asphalt construction projects to be executed differently in the future. These themes include:

A. *Technology introduction and adoption*

Through alternating steps of technology introduction and making operational strategies explicit, the construction team gradually become used to new technologies and the benefits that new technologies bring to adopting more professional method-based work strategies. Experiments of new technology introduction have in the past showed problems of adoption. To be adopted the technology should be tailored to the prevailing operational strategies, but at the same time the technology has to be adapted to make the prevailing operational strategies tangible. Appropriate strategies need to be devised to overcome this causal dilemma. Part of the solution lies in the involvement of the construction team in technology development efforts. Rather than just being recipients of technology, they need to be part of the development of technology and the technology of methods.

B. *The use of visualizations*

Currently, communication between construction parties relies mainly on drawings and specifications. Visualization, on the other hand, makes communications more effective and accessible [9]. Combining new technologies and appropriate visualizations permits studying the asphalt construction process from operational perspectives which in turn, enables a deeper understanding of operational behaviour and more importantly, of variability. Layers of data production become a catalyst for deeper understanding for those closest to the action, designers, planners and operators. The more data-rich approach to asphalt construction opens up new strategies for combined technology and skills development, enhancing the effectiveness and adoption of new technologies in road construction. Key is that the visualizations focus on process parameters such as mix temperature and compaction, which operators implicitly know have an effect on the final quality of the pavement [20]. The tacit knowledge, normally hidden, is made explicit and useful.

C. *A focus on and, increased opportunities for process improvement*

Currently, the absence of "feedback systems" for quality assurance [21] is a serious shortcoming in asphalt construction and creates a barrier to continuous improvement and learning. Designers and construction teams need to be involved in, and take responsibility for process improvement since they are largely responsible for the success of the construction process. Hard process data provide the basis for them to critique their own performance leading to opportunities for process improvement.

D. *Real-time process control*

It is debatable whether current quality control practices or stringent "as-built" testing provides confirmation that the process was indeed "in-control" during construction. It appears that it mostly provides confirmation of an end-result [5]. There is hence a need to firstly, monitor whether the process is "in-control" and secondly, for the acceptance testing to provide confirmation that the process was indeed "in-control". More importantly, while the suggested data and visualizations are invaluable for process improvement, identifying the opportunities for improvement has to take place in "real-time" since this is the only opportunity to "get it right".

E. *Permanent georefencing of construction activities*

Practitioners are generally concerned with not being able to trace operational discontinuities in the actual construction process. Since key process parameters cannot be traced back spatially, little learning takes place from project to project, the result of which is that similar operational mistakes are made repeatedly and implicit practices based on tradition and custom continue. Also, most current project information is captured in documents. The process-driven approach bypasses the paper work route using an electronic environment. This approach is a means of sharing project information via a shared process model between key role players involved in the construction process. Important is that the full array of registered data can be used to develop maintenance strategies, strategies for new construction and continuous process improvement initiatives.

F. *Increased opportunities for simulation*

Two simulation challenges are drawn from the scenario. The first is designing appropriate compaction strategies since current laboratory procedures make little attempt to simulate the actual compaction process and thus, a need to better align laboratory and field practices. With this paper mainly focusing on process improvement, the reader is referred to [22] for a proposed laboratory design framework that better simulates site compaction. The second issue is related to training and planning for asphalt paving and compaction. As far as is known, other than [23, 24], few asphalt construction simulation tools exist that can be used for training and planning purposes. The suggested architecture could include simulation tools based on actual data and improve collaborative working strategies related not only to paving and compaction but also to other construction activities. It has the potential to form the basis of education and training and the successful transfer of practical knowledge and technology.

G. *Changing roles*

The successful implementation of the proposed vision and the new ways of working will require different skills of all involved in the process. In road construction, roles have traditionally been seen as separate e.g. pavement designer, logistics planner and site manager. However, proper process control requires a more integrated approach to the presented challenges to deal with design, laboratory, planning, improvements and maintenance. Changing roles and responsibilities will result in retraining and education at all levels of the workforce. The attitude of "that's the way we've always done it " will no longer be acceptable and an openness and input to new ways of working will be expected [8].

Also, the perception that road construction projects are often unique and lessons learned are not readily transferable, results in very little re-use of construction project knowledge. Real-time capturing and the permanent georeferencing of data provides significant opportunities for knowledge transfer and training. The extension of knowledge management systems to all workers could dramatically increase the number of people inputting into the knowledge bank [8] and result in the development and retention of more explicit, method-based practices.

H. Decision-making at various levels.

Companies in general need to make operational, tactical and strategic decisions based on hard evidence. From a management perspective, actual process data helps management (executives) more deeply understand what is happening on the construction site, prioritise and support process improvement initiatives and act on strategic issues. This in turn, makes it possible for companies to reshape their competitive advantages.

V. A Vision Based on the Dutch Experience

The scenario we paint is achievable in the not too distant future. It is based on several years of studying live projects, hard data and the construction process from technology, process and people perspectives. It is our view that current sensor technologies have advanced far enough and have for the past few years shown a rapid enough rate of advancement for the Construction Site of the Future to become reality. However, there are important issues to take into account when developing appropriate process control systems including:

- The dangers associated with developing closed systems, the absence of standards and the lack of interoperability between current systems
- The potential threats including barriers to technology adoption and the cost of new technologies where smaller companies may have a greater need for the technology, but cannot afford it [9]
- The fragmented nature of the construction industry
- The lack of clear leadership and knowledge in the development, application and implementation of process performance systems
- The absence of dealing with all levels of decision-making i.e. operational, tactical and strategic
- The mismatch in the requirements of clients, designers and contractors
- The absence of appropriate education and training to implement improvements

While an extensive cost-benefit analysis has not been explored for this paper, we believe that the investment in new technologies and its integration in asphalt construction can be justified with several potential benefits including: (a) improved process control and therefore less variability, (b) longer asphalt pavement service life, and (c) less expensive maintenance requirements.

Also, there is a need for the asphalt construction industry in its entirety to move into the knowledge society. For this to happen, the industry needs to be able to build upon an existing information base. Sadly, this information base is either lacking or widely dispersed given the islands of information approach so often adopted and encouraged in the construction industry [8]. Machine manufacturers, IT developers and asphalt professionals all want to contribute to the design and construction of durable asphalt pavements. However, the difference in approaches and mismatch between appropriate technology and the needs of the industry has contributed to the lack of useful operational, tactical and strategic data which in turn, has resulted amongst others in considerable variability. Does this mean that the industry must adopt a "one-size fits all" solution to the challenges faced? Certainly not. This would be anti-competitive, totally unrealistic and very difficult to manage. Rather, the aim must be to develop systems that focus on process control and improvement that enables sound, informed decision-making at all levels.

The Dutch experience has matured through a route of combined experimentation with contractors and researchers actively participating in process improvement endeavours. Role players have combined to address the overall issues of variability and the need for process improvement. Importantly, rather than just being recipients or users of technology, role players have become part of the development of appropriate technology, the technology of method and have widely adapted, adopted and incorporated new technologies in the asphalt construction processes. This has resulted in a fairly consistent view of what to aim for in the future. It is from this joint platform that we propose a Construct Site of the Future for the asphalt industry and how new technologies combined with appropriate construction informatics systems may benefit the industry. What is clear is that the any future system should include:

- Appropriate data processing and visualizations,
- Early warning software systems that identifies preventable process variability,
- Decision-support modules enabling real-time information flow between operators and other key site personnel to effectively manage data in real-time,
- Modules managing data for post-construction analysis, and

- Appropriate education and training to make advances in technology, people, processes and organisations.

VI. Conclusions

The rather unique mix of contractors (willing to open themselves up to scrutiny) and researchers making up ASPARi has for the past 8 years shared research challenges, outcomes and significant progress. Considerable progress has been made in understanding how to address challenges facing asphalt construction including how to bring design, construction, technology and innovation closer to each other. The research has moved through a trajectory of intense experimentation. It includes making operational behaviour explicit through using new sensor technologies, bringing the technologies closer to asphalt teams and importantly, addressing the gap between laboratory and field practice.

We believe that the main issue facing asphalt professionals in the industry is variability. The introduction of appropriate informatics in asphalt construction and subsequent decision-making based on hard, evidence-based data provides the means to confront most of the issues faced with variability in key process parameters, including mix temperature and compaction. In this research, the step-wise introduction of technology to firstly make operational behaviour explicit and secondly, to use these to develop method-based operational strategies, has led to the adoption and incorporation of several new technological innovations in construction practices. This has led to the sidestepping of problems associated with technology adoption and the breaking down of barriers to technology adoption so often referred to in the last decennia. Also, there is a much greater sense of shared understanding between researchers and contractors of the vision of the future and how to deal with the challenges facing the asphalt construction industry.

Perhaps most important, is our view that this vision can only be realised if Public Clients take the lead in stimulating innovation and creating the space to innovate. There is general agreement that public clients play a critical role in the construction innovation process and that clients' sponsorship is essential for the successful implementation of construction innovation [25]. This prominent role allows them to stimulate and support the development and implementation of innovative solutions to challenges of process performance [26, 27]. In The Netherlands, public clients have introduced new contracting schemes containing incentives for better quality of work [28] and successfully introduced several programs whose aim it is to stimulate innovation in the construction industry [29, 30].

Construction companies in turn, faced with new types of contracts, tougher competition and the urge to make a distinction in the market, are motivated to advance in product and process improvement. The contractual changes have significantly altered the playing field for competition. The companies see themselves confronted with different "rules of the game" than what they were used to. Performance contracting and longer guarantee periods in particular, create a new set of risks and business incentives. Dutch construction companies have consequently, actively pursued taking control of their primary processes. They understand the need to have better control over the design and the construction process, over the planning and scheduling of resources and work, and over performance, in order to reduce the risks of failure during the guarantee period. As a result, they currently take a more integrated approach to the planning and design of logistics, paving and compaction strategies. This should lead to less variability and therefore improved quality in the future.

Acknowledgement

The authors would like to thank the contractors aligned to the ASPARi network for providing access to their asphalt construction projects and for continuous fruitful discussions regarding the construction site of the future.

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