Computers in Industry 121 (2020) 103264

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Peeking into the void: Digital twins for construction site logistics

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ARTICLE INFO

Article history:
Received 31 December 2019
Received in revised form 20 March 2020
Accepted 15 May 2020
Available online 10 July 2020

Keywords:
Digital twin
Decision support system
Construction industry
Supply chain management
Smart logistics

ABSTRACT

Construction is one of the least-digitized industries in the economy. To rein in the rising costs of building activities, digital transformation is one of the pillars that industry leaders rely on. A case in point are logistics processes which are characterized by very limited visibility and inefficient organization. To progress beyond this current state of the art, we conceptualize the idea of a lightweight digital twin for non-high-tech industries. In collaboration with a leading supplier of building materials, we explore the opportunities offered by digital silo twin capabilities. Focusing on fill level monitoring we identify diverse opportunities for generating informational, automational and transformational business value. Leveraging new information sources for the redesign of core business processes drastically increases the complexity of operational decision-making. To tap into these opportunities, we design and implement a decision support system for silo dispatch and replenishment activity.

1. Introduction

Significant improvements in information and communication technologies (ICT) including cloud computing, Internet of Things (IoT), as well as artificial intelligence (AI), have already disrupted many sectors (Drucker, 2017). Drawing on these technological innovations the digital twin concept – a digital representation of a physical object of interest – has recently emerged as a particularly attractive use case across various industries (Cimino et al., 2019). The investment in digital twins is expected to be offset by increased productivity through predictive analytics (Lee et al., 2013) or the provision of value-added services (Tao et al., 2018). However, oftentimes these goals cannot be achieved by mere data collection but necessitate the adoption of data-driven decision-making (Davenport and Harris, 2007; Brynjolfsson et al., 2011).

Such solutions already create significant business value (Cimino et al., 2019; Cearley et al., 2016; Boschert and Rosen, 2016). Current applications share the fact that they are typically deployed in technology-oriented industries where companies are used to operate on the front-line of innovation. In contrast, "low-tech" industries are much less frequently leveraging the potentials of digital transformation. At the same time, these industries are of great importance to any developed economy (Hirsch-Kreinsen et al., 2006).

A case in point is the construction industry which is frequently listed among the least digital industries (Leviäkangas et al., 2017). Yet, digital transformation is expected to significantly reshape this industry in the years to come (Oesterreich and Teuteberg, 2016). Currently, many players in construction are pushing forward digital representations of buildings to facilitate easier management, maintenance and upgrading (Song et al., 2012; Khajavi et al., 2019). However, construction site processes remain distinctly non-digital characterized by unclear responsibilities, printed plans and opaque inventories. In such environments efficient planning procedures are difficult to implement.

In collaboration with a leading supplier of building materials, we explore the opportunities for construction site logistics offered by establishing digital twins for bulk silos. We are interested in the potential business value of continuous silo fill level monitoring and tracking. This seemingly small technological innovation offers several opportunities for improving current and introducing new business processes.

This paper is structured as follows. In Section 2, the supply process is described, followed by the shortcomings of the status quo. Section 3 will elaborate on the related work. Then in Section 4 the business value opportunities of this nascent information system are presented. In Section 5 the process transformation is presented, followed by Section 6, where the decision support system (DSS) used to tap into these transformational benefits and its results are discussed. The final section concludes and provides an outlook for future research.

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https://doi.org/10.1016/j.compind.2020.103264
0166-3615/

2. Problem description

Bulk materials constitute the largest element of the construction supply chain (Lundesjö, 2015a). The storage of these materials needs to be cost-effective, safe, and systems should be easy to integrate into operational processes. Bulk silos have established themselves to be particularly suitable for mobile bulk storage applications in construction and agriculture. This is also the case for the industrial partner we collaborated with in this research.

2.1. Supply Processes

Given the context, the standard silo supply process depends on hauling silos back and forth between constructions sites and material production plants. This silo movement process is organized as follows (compare Fig. 1a):

1. Silo is filled and weighed at the plant.
2. Logistic operator trucks the silo to the construction site where the contractor requested the material.
3. Silo is picked up and returned to plant by logistics operator upon deregistering by the contractor. At the plant, the silo is weighed again. The contractor is billed the difference between the original fill level and the remaining material.

Besides this standard process there is a replenishment process for situations where construction site demand exceeds the volume of a single silo. The replenishment process steps are as follows (compare Fig. 1b):

1. Contractor signals replenishment requests upon emptying a silo.
2. A tanker truck brings a weighed amount of material to replenish the silo. The replenishment amount is included in the bill upon deregistering and returning of the silo.

Note that weight-based billing necessitates that a silo always has to return to the plant prior to switching customers—even if the remaining fill level is sufficient to serve a subsequent customer.

2.2. Shortcomings of the status quo

The described processes are representative across the bulk construction materials industry. They have emerged from a combination of regulatory requirements (exact weighing), contractor behavior (ad-hoc requests of material), and plant locations. They can be considered a form of "optimal coping" with a difficult situation. It is easy to see that there are a number of shortcomings related to this setup:

- *Excessive silo movements* between sites and plant. This is particularly evident for construction sites in sprawling urban development areas where there are ample subsequent business opportunities. The problem is amplified by the fact that silo-moving trucks require expensive and maintenance-intensive lifting facilities. Furthermore, silos are unproductive during these lengthy movement activities which inflates the silo stock.
- *Risk of work interruption* at large construction sites because of opaque fill level. Replenishment can only be triggered when contractors realize that a silo is depleted. This will typically interrupt work until the replenishment is completed, which puts a lot of pressure on the supplier to handle these requests as quickly as possible.
- *Impaired operational planning* because of bad forecast quality. This is due to irregular and discrete orders. Silos are positioned at construction sites over several weeks during which the supplier has no information on material usage. Returned unused material may be too old for further usage.

Besides these direct problems arising from the bulk distribution system there are also long-term ramifications. The established way of handling these operations prescribes the silo design (capacity should match demand of a typical construction site) as well as the composition of the transportation fleet (many expensive silo-movers, few tanker trucks).

3. Related work

The advances in information and communication technologies lead to the integration of more and more functions into supply chains. Consequently, supply chains and logistics systems become more comprehensive in the practical and theoretical world. Being concerned with digital innovation for construction site logistics, we investigate three research strands: Trends in the construction industry, digital twin strategies as well as vehicle and inventory routing problems.

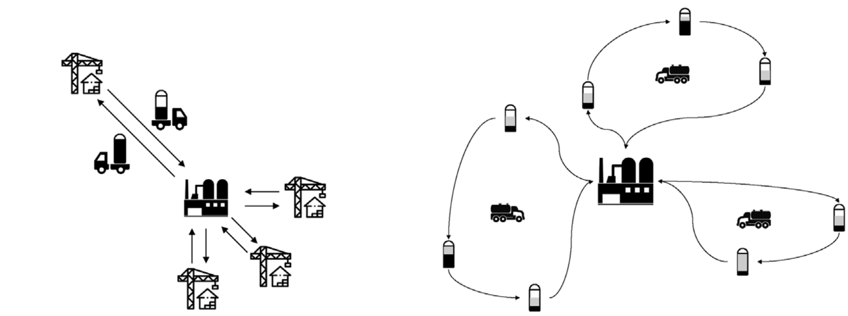
3.1. Construction industry

Labour productivity in construction has declined over the last decades, while other manufacturing industries have nearly doubled its productivity at the same time (Teicholz, 2013). Companies from the construction industry have not managed to integrate digital technologies to keep up with their counterparts from the automotive or mechanical engineering sector (Kraatz et al., 2014). In recent years, optimization approaches have been increasingly applied in civil engineering, most often for problems under complete information (Dede et al., 2019). The decentralized organization of the construction companies as well as the temporary nature of the construction projects are barriers to innovation for online planning problems (Oesterreich and Teuteberg, 2016; Dubois and Gadde, 2002). For example, material supply is often excluded from supply chain management, because it is coordinated by the various commercial subcontractors, which are engaged in a fixed price (Lundesjö, 2015b). Due to the high fragmentation in the supply chain in terms of a high amount of small and medium-sized firms with undifferentiated products and services and limited capabilities for investments in new technologies (Kraatz et al., 2014; Arayici and Coates, 2012), it is important to integrate low-cost technologies (McFarlaneet al., 2019).

The innovative power of low-tech companies is often bottlenecked by the lack of transparency and digital connectivity (Dallasega et al., 2018). With the right tools, these companies can also tap into the potential of new digital and analytical capabilities (Flath and Stein, 2018; Gust et al., 2017).

3.2. Digital twin

The challenge in fragmented supply chains is to make dynamic and real-time decisions. Therefore, silos must be continuously tracked and monitored (Montreuil, 2011). Real-time data embedded in IoT with abundant computing power and optimization assist such dynamic supply chain decisions (Büyüközkan and Göçer, 2018; Jedermann et al., 2006). Digital twins – digital representations of physical objects – consider information to be a replacement for wasted physical resources (Grieves and Vickers, 2017). Similar approaches already existed before the emergence of the digital twin (Grieves, 2005). The digital twin concept, however, is strongly related to IoT and combines the digital representations with intelligent connections such as algorithms and simulations to consolidate the enormous amount of information and data from different sub-



(a) Silo movement process

(b) Replenishment process

Fig. 1. Status quo.

systems and to make dynamic and real-time decisions (Grieves and Vickers, 2017).

Digital twins are developed for various physical objects. Manufacturing companies use digital twins to collect data about the product life-cycle and leverage them for product design (Tao et al., 2018) or predictive maintenance (Vachálek et al., 2017). Digital twins control and optimize the drilling process in real-time (Mayani et al., 2018). In aeronautics, individual components or entire systems are designed and developed virtually (Glaessgen and Stargel, 2012; Tuegel et al., 2011). Health applications combine wearable medical devices and digital twins for monitoring and diagnosis (Liu et al., 2019). Kampker et al. (Kampker et al., 2019) initialize a product-service system for potato harvesting. We classify digital twins according to their application and complexity. Klostermeier et al. (Klostermeier et al., 2019) identify three application areas: simulation in the development, operation of products and systems, and product life-cycle management. Extending the perspective of Negri et al. (Negri et al., 2017) we distinguish between three levels of complexity:

- *Lightweight digital twins* reflect simple structures and do not contain unnecessary details, this reduces the size and allowing fast processing (Boschert and Rosen, 2016; Grieves, 2014).
- *Multi-physics, multi-scale simulation systems* combine models, data and information (Shafto et al., 2012).
- *Autonomous systems* enable decision automation without reconfiguration even for unexpected situations. Rosen et al. (Rosen et al., 2015) describe the digital twin as “the next wave in modeling, simulation, optimization technology”.

Digital twins consist of at least the digital representation of the physical object and make the data intelligently usable for different applications. Integrating a lightweight digital twin into a DSS can be the first step to leverage the potentials of the digital twin even if not all data and information is fully integrated (Boschert and Rosen, 2016; Kunath and Winkler, 2018).

3.3. Silo and inventory routing

To model the supply chain of returnable silos, we adapt the general pickup and delivery problem (PDP) of Savelsbergh and Sol (Savelsbergh and Sol, 1995). Trucks have a capacity for two silos, hence our capacitated PDPs are strongly related to the full-truck-load category (Parragh et al., 2008a). Silos have to be loaded in the depot and all picked silos have to be transported to the depot. Parragh et al. (Parragh et al., 2008b) classify this as a multi-vehicle routing problem with mixed line-hauls and back-hauls (VRPMB). According to Berbeglia et al. (Berbeglia et al., 2007) this problem belongs to the class of PDPs with a one-to-many-to-one (1-M-1) structure. Thereby the transport of empty silos is rather the rule than the exception (Kroon and Vrijens, 1995).

Redesigned business processes enable delivery with every picked silo of the same commodity, a multi-commodity PDP (Hernández-Pérez and Salazar-González, 2009). Berbeglia et al. (Berbeglia et al., 2007) classify this PDP with unknown pickup points and quantities as unpaired many-to-many (M-M) PDP. Since all vehicles depart and end up at the depot, we adopt the notation of Van Anholt et al. (Van Anholt et al., 2016) and classify our problem as capacitated multi-commodity VRP with unpaired one-to-many-to-many-to-one pickup and delivery (CMVRP-(1-M-M-1)-PD).

Using the operated silos as stocks push the material into the urban development areas. The supplier periodically makes inventory replenishment decisions for the silos. These decisions require inventory management systems with silo fill level monitoring and tracking. In addition to inventory, data-based forecasting can be integrated into the decision-making process (Holmström et al., 2002). Besides inventory costs (holding and handling), transport is a decisive cost factor. The inventory routing problem (IRP) therefore integrates vendor-managed inventory management, route planning, and scheduling decisions. Typical IRP examples are the delivery of petroleum products to petrol stations with tanker trucks (Cornillier et al., 2009) and cash replenishment in an automated teller machine (ATM) network (Kurdel and Sebestyénová, 2013).

4. Digital supply chain

Having outlined the status quo, we next want to explore how the company’s business operations may benefit from expanding the digital representation of their silos. Currently, the company tracks for each of its silos the type (size, dispenser system), the material currently filled in, and the position (based on order status). To achieve a complete digital representation—a proper digital twin of the silo—one needs to be able to access the silo’s current fill level. Clearly, the integration of such monitoring capabilities requires upgrading silos with fill sensors and suitable connectivity capabilities.

Upgrading a large stock of silos requires major investments which need to be carefully evaluated. Decision makers should consider the initial (efficiency gains that result from the automation of a process), intermediate (more informed decision-making) and long-term (process optimization and organizational learning) benefits that could arise from the use of information systems (Scheepers and Scheepers, 2008). While the emphasis is on the focal business process, benefits to and from other value linking and acceleration processes should also be considered (Parker et al., 1988). Porter et al. (Porter and Millar et al., 1985) distinguishes three perspectives of how value is created within the theoretical views of the value chain framework: Changing the structure of the industry, creating competitive advantages and spawns whole new companies.

To assess the benefits of this nascent information system we adopt the framework proposed by Mooney et al. (Mooney et al., 1996) which groups benefits of information technology (IT) based on their scope – informational, automational and transformational.

4.1. *Informational benefits*

Informational effects correspond to IT-driven information collection and dissemination which in turn improves decision quality, resource utilization, and organizational effectiveness (Mooney et al., 1996). Continuous tracking of silo fill levels is a straightforward candidate for this dimension as sporadic information updates (weighing at the plant) are superseded by comprehensive monitoring. So far, the company improved their core operations processes through best practices and rules of thumb. The availability of comprehensive data creates the opportunity to optimize based on facts instead of gut feeling. Direct operational benefits from being able to monitor the construction site include better demand forecasting as well as correct inventory records across the silo fleet. Furthermore, customer insights can assist the sales staff in targeting and communication while product managers can tailor product and service offerings to better match what the customers actually want. Finally, customers can be offered simple descriptive analytics services (apps, dashboards) that allow easy monitoring of consumption and accrued costs.

4.2. *Automational benefits*

Automational benefits originate from productivity improvements and cost reductions. Currently, silo replenishments are only triggered when a silo is depleted. This will typically interrupt work until the replenishment is completed. This pressures the supplier to handle replenishment requests as quickly as possible. In turn, operational planning of replenishments is performed on a short time horizon as orders arrive without any lead-time. The possibility to assess the fill level of a silo paves the way towards more efficient replenishment processes. In particular a threshold-based preemptive replenishment policy can be adopted where replenishments are triggered as soon as a certain fill level is reached avoiding depleted silos at the construction site (better service level and higher customer satisfaction). Automated weighing and reporting also creates productivity gains from faster silo handling and smoother production plans. Similarly, billing processes can be automated. Last but not least, complete operational data availability equips management with a real-time decision basis. Such information can be leveraged for price negotiations and investment planning.

Table 1
Business value opportunities facilitated by the digital silo twin.

Scope	Functionality and impact
Informational	Continuous asset tracking
	Improved customer insights and strategic planning
Automational	Threshold-based preventive replenishment
	Data-driven reporting and automated billing processes
Transformational	Adoption of new logistic processes
	Transformation from product to service offering

4.3. *Transformational benefits*

These benefits refer to the value deriving from opportunities for business process innovation and transformation created by the availability of IT systems (Mooney et al., 1996). In the status quo processes most silos spend a lot of unproductive time on the road venturing back and forth between the plant and the dispersed construction sites. However, there is regularly clustered construction activity in certain locations. Being able to forego weighing at the plant for billing purposes allows repositioning the silos from one construction site to another. To compensate for material consumption this would, in turn, require more extensive usage of silo replenishments.

From a managerial perspective, such a switch towards silo repositioning plus replenishing in the field entails a complete redefinition of the company's business transactions: Historically, customers ordered a silo with a certain amount of material which they wanted to utilize. Going forward, the supply paradigm may switch to a material-as-a-service regime where construction sites obtain material from silos without ever placing an order.

Table 1 summarizes the possible benefits offered by the introduction of smart silos. Note that the informational and automational benefits can be realized fairly quickly after the introduction of silo digital twin technology. However, leveraging the transformational benefits is more complex as it requires establishing significant changes to current business processes.

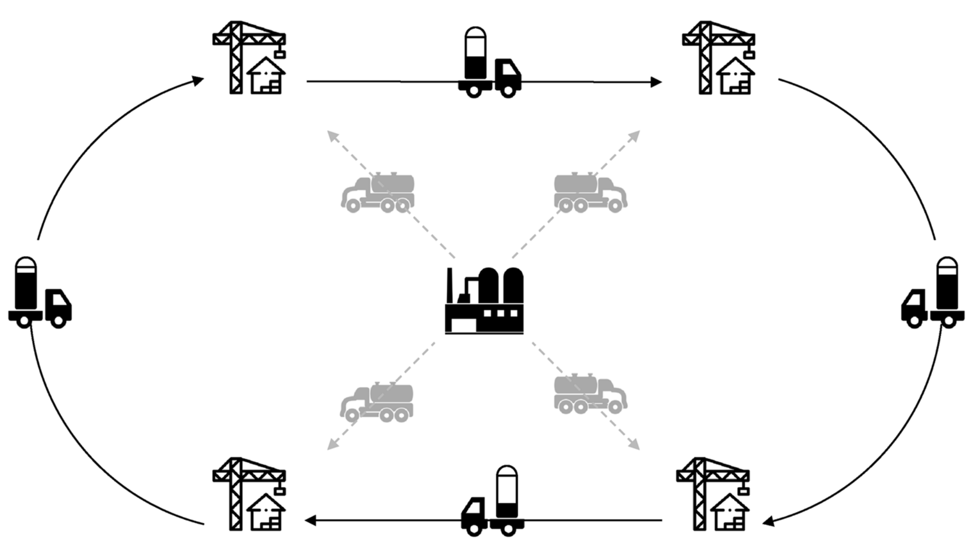


Fig. 2. Integrated supply process.

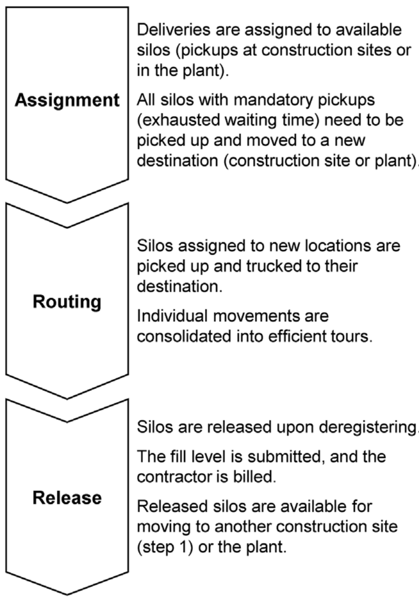


Fig. 3. Silo repositioning and routing process.

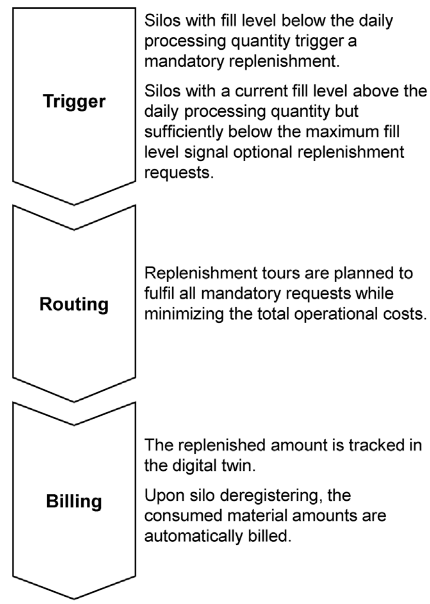


Fig. 4. Replenishment process.

5. Process transformation

Utilizing the available data allows us to break up the existing silo supply and replenishment processes described in Section 2. In contrast to the old plant–site–plant movement patterns, the additional available information allows to move silos directly between construction sites, see Fig. 2.

5.1. Silo repositioning and routing

The new silo supply process requires to decide which silo is transported to which construction site on which truck during dispatch. At the same time, a variety of operational constraints, such as capacity and weight limits for trucks and silos, maximum idle placement periods, or maintenance intervals, have to be respected. The new process is organized as shown in Fig. 3.

With complete information on future orders this planning problem corresponds to a capacitated multi-commodity vehicle routing problem with unpaired one-to-many-to-many-to-one pickup and delivery (CMVRP-(1-M-M-1)-PD).

5.2. Replenishment planning

In addition to silo repositioning, the new process gives rise to an additional planning problem. With real-time information on the current fill level of each silo, planners have to decide which silos are to be replenished with which quantity and by which tanker truck. In order to guarantee continuous construction, every silo with a current fill level below the daily processing quantity has to be replenished. Additionally, all silos with free capacity allow an optional replenishment. These optional replenishments can reduce the total operational costs as they increase the utilization of the tanker trucks and help to avoid underutilized tours at a later point in time. The new replenishment process is organized as shown in Fig. 4.

This decision problem can be modeled in the sense of a multi-compartment inventory routing problem with continuously flexible compartment sizes (MC-IRP-FCS).

5.3. Operationalization of integrated process

Under complete information both aforementioned sub processes can in principle be mathematically modelled and solved exactly. However, this is not a suitable approach in our context for multiple reasons:

- The silo repositioning and routing process in Fig. 3 requires variables x_{ij}^{kt} to indicate that the connection between construction sites i and j is used by silo-mover k at day t. The replenishment process in Fig. 4 requires variables y_{ij}^{vt} to indicate that the connection between construction sites i and j is used by tanker truck v at day t. The isolated sub processes are computationally hard problems and exact solution are limited to very small problem instances (Lenstra and Kan, 1981). Even for an far unrealistic scenario with only 100 construction sites and 5 working days as well as each two silo-movers and two tanker trucks, there would be $100 \times 99 \times 5 \times 2 \times 2 = 198,000$ decision variables which results in numerous necessary auxiliary variables and constraints.
- Repositioning and replenishment process are inherently coupled by the daily fill level f_s^t and the assignment a_{si}^t of the silo s to the construction site i.
- Complete information is not available in the described setting, particularly due to short notice ordering and uncertain consumption behavior of customers.

Consequently, we must consider a heuristic optimization approach to tackle the integrated problem embedded in a holistic process transformation. In particular, we choose a sequential approach where we first optimize repositionings and subsequently determine optimal replenishments. For the repositioning problem, we follow Fisher and Jaikumar (Fisher and Jaikumar, 1981) and implement a cluster-first route-second heuristic. Vacant silos that require a pickup, as well as deliveries requested by customers, are clustered based on their geographical locations. Based on these clusters we implement the process from Fig. 3:

1. Vacant silos are assigned to known future orders on a daily basis. Backhauls due to maximum idle placement periods should be avoided. Therefore, we solve an assignment problem with time-dependent weights for prioritizing between mandatory pickups

and deliveries, which must be carried out at the latest today, and optional pickups and deliveries.
2. The fixed assignment reduces the complexity of our problem as we now consider paired pickups and deliveries on a daily basis. In addition, optional repositionings are only executed today if they are in line with efficient tours. The reposition routing module heuristically solves several small instances (each day one for each cluster) of the capacitive vehicle routing problem with selective paired pickup and delivery (CVRP-SPPD) (Parragh et al., 2008b).

To determine efficient replenishment tours we adapt the savings algorithm from Clarke and Wright (Clarke and Wright, 1964). To implement the process from Fig. 4 we modify the algorithm by weighting the distances of the potential replenishments with their potential quantities. In addition, we let the algorithm terminate once all mandatory replenishments have been assigned to tanker trucks.

6. Results

Due to the large number of decision variables and constraints, the complexity of the new integrated process may easily overwhelm a human decision-maker. We seek to design a suitable DSS to leverage the transformational benefits of smart silos and support planners in their operational and strategical decision making. Subsequently, we exploit the prototype DSS to perform extensive simulations.

6.1. Decision support system

Our DSS is building on the digital twin, as visualized in Fig. 5. We demonstrate its functionality for a regular day with pickups, deliveries, and replenishments. In addition to relevant numerical results, the structured and visual presentation of the insights is a key component of a strong DSS. Therefore, the operational interface provides various visualizations and tables that support the logistics in the operative decision-making process. The prototype interfaces for the step-by-step planning are illustrated in Fig. 6 for the silo movement and in Fig. 7 for the replenishment process.

Silo and order overview: The first planning screen in Fig. 6a shows the geographical location of all free silos as well as their current fill level based on real-time information provided by the digital twin. As additional information, the silos requiring a mandatory pickup are marked separately. For the assignment, all outstanding deliveries and plants are displayed in parallel. The central plant from which the material is to be supplied is displayed in a different shape. The fully automatic assignment proposals are directly visualized in this view and can be manually modified or accepted. Due to technical constraints of the silos, this view is material-specific.

Repositioning routes: Based on the assignments, the system determines possible truck routes and visualizes them as shown in Fig. 6b. At this point, the user can accept the proposal, add deliveries or pickups manually or modify the routes of the repositioning trucks. In contrast to the silo assignment, the routing is performed for all materials and silo technologies at once.

Replenishment overview: To support the replenishment process, the planner is provided with a visual representation of all silos in the field. As visualized in Fig. 7a, this view shows the current fill level as well as expected remaining time until the release of all silos. Additionally, silos with mandatory replenishments as well as silos with replenishments proposed by the system are highlighted.

Replenishment routes: Based on this information, the system determines possible replenishment tours as illustrated in Fig. 7b. Similarly to the silo repositioning routes, the planer can either accept the proposals or perform manual adjustments.

6.2. Numerical studies

Strategic decision support is primarily founded on the analysis of historical data. Simulations based on the data of the last three years for various plants show that the total truck costs can be reduced by 25% compared to the status quo, see Fig. 8. The naive approach of moving silos directly between construction sites and operating threshold-based replenishment provides an additional benchmark. Tanker trucks are standard transport technology, so that replenishment services can be outsourced to third-party suppliers charged at a fixed cost rate (€ per kilometer). Silo-moving trucks must be modified with special lifting facilities. Therefore, the company has to operate these trucks, causing fixed investment (€ per truck and year) and variable operating costs (€ per kilometer). The simulations appear to be sensitive to these cost parameters. For example, increasing demand for tanker trucks may affect their cost rate. The various plants differ in terms of distribution volume, delivery distances, and product mix. We observe that the potential cost reductions are strongly related to these structures. From Fig. 8 we identify two different types of cost saving potentials:

1. straight-forward reduction by the naive approach of moving silos directly between construction sites,
2. leverage digital twin data for live-updated smart replenishment decisions.

The naive approach can lead to additional costs due to inefficient replenishment processes. Both the degree of transformation and the complexity of the digital twin have a significant impact on costs. Possible unprofitable investments today also represent an investment in the future and the corresponding business model can improve efficiency and thus reduce operating costs (Klostermeier et al., 2019). When companies decide to introduce data-based decision support systems, it is important to train their employees not only in the use of the new system but also in the new business processes associated with it.

From the cost structure, Fig. 8, we observe a shift in the infrastructure. Since the silo-movers are now operated regionally, fewer trucks are needed. At the same time, the new logistics system increases the number of tanker trucks operated, as the silos are now predominantly replenished at the construction sites. The outsourcing of transport distances is a pillar that industry leaders rely on to curb rising transportation costs (Batarlienė and Jarašūnienė, 2017).

7. Conclusion and outlook

Our research does not simply explore the potentials of digital twins within a low-tech industry, it also sheds light on how that value is provided through intelligent decision support. With the limitation that our findings rest on a single case company. By transforming “dumb” silos into smart data processing units a new logistics system can be established which can directly reduce costs. Also, every kilometer saved has a positive effect on the development of CO_2 emissions (Léonardi and Baumgartner, 2004). The installation of the sensors enables permanent silo tracking and threshold-based filling. The sensors facilitate the process transformation towards direct silo repositioning with limited back-haul traffic. However, retaining a naive threshold-based replenishment policy does not necessarily lead to cost reductions. For this reason, the new logistic system can only fully achieve its whole potentials through the combination of silo and inventory routing in a

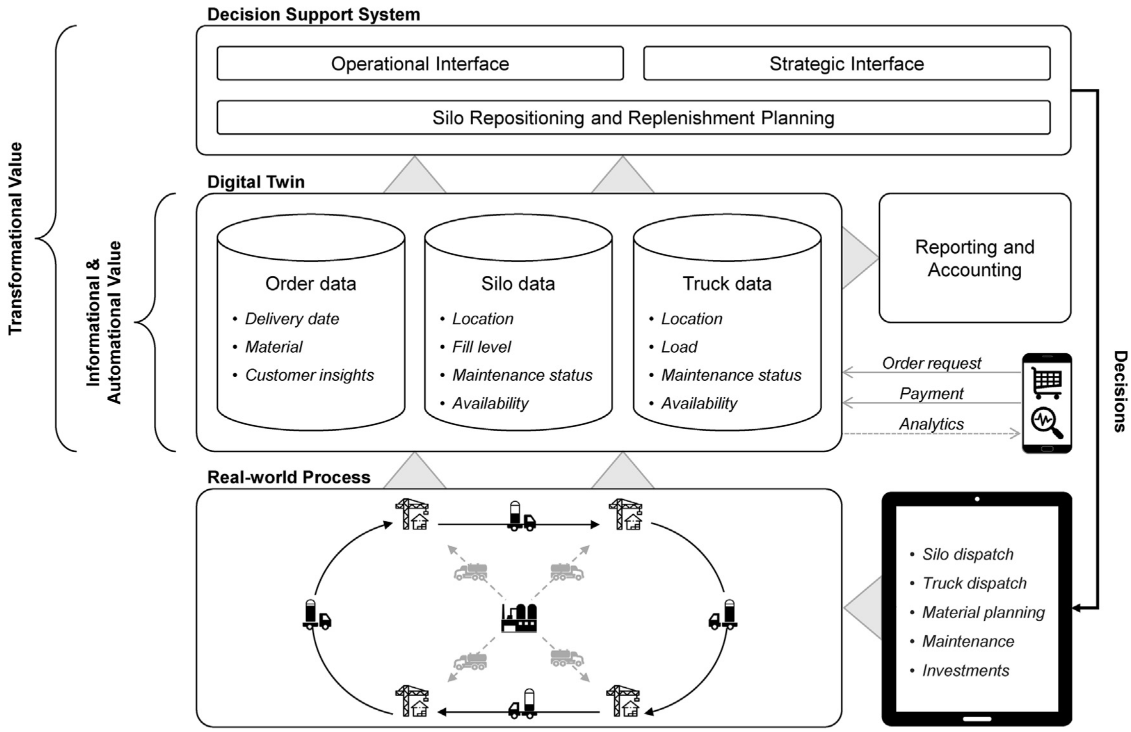
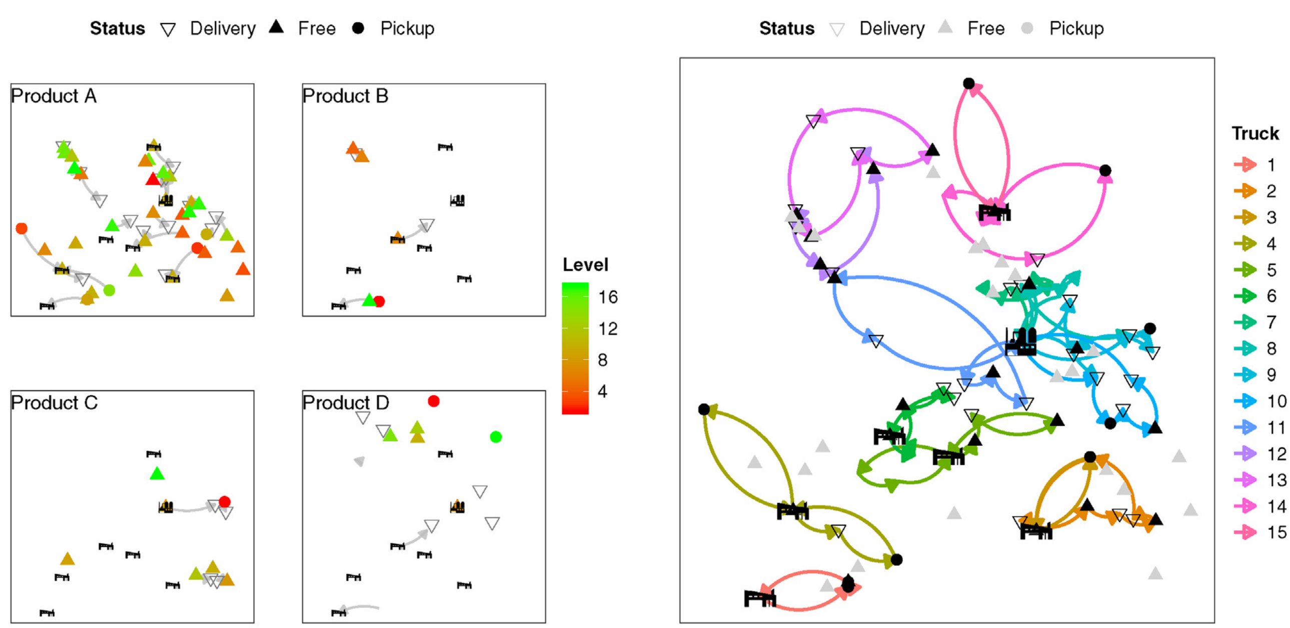


Fig. 5. System design and system information flow.



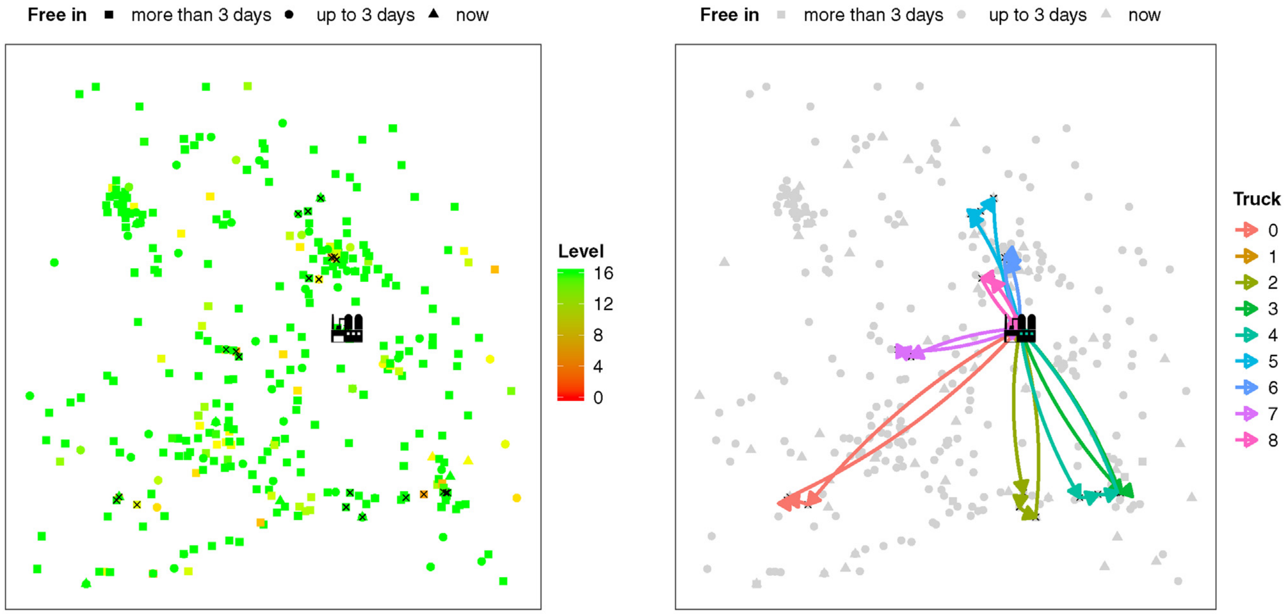
(a) Silo and order overview

(b) Repositioning routes

Fig. 6. Process demonstration – silo movement process.

dynamic setting. Although the PDP as well as the IRP are established problem classes in research, the complexity of the embedded dynamic optimization problem raises a new topic of interest. The narrow gap between success and failure in this project highlights the importance of this research.

The new policy reshapes relations between central plants and distributed depots. The material supply must continue to come from the plant, but all other tasks (maintenance, repositioning, intermediate storage) of the silo-movers and silos can be carried out regionally. To exploit the full potential of the new logistics system in the long term, the company has to align future investments (infrastructure as well as operating assets) with the operational practices. Our DSS simulates different maintenance intervals, new strategic locations, various fleet configurations over varying ranges of service level requirements. Based on these simulations the company started to restructure its truck and silo fleet. A major driver of logis-



(a) Replenishment overview (b) Replenishment routes

Fig. 7. Process demonstration – replenishment process.

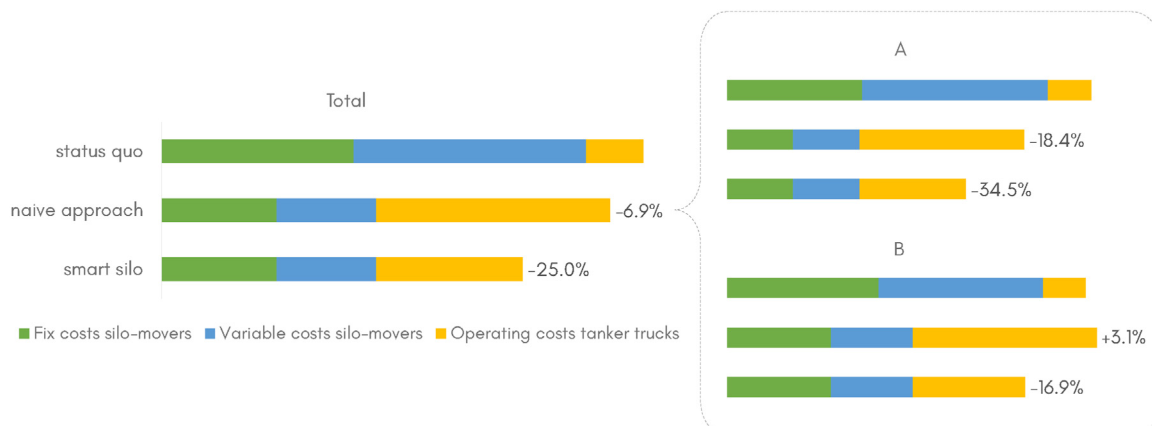


Fig. 8. Total truck costs.

tics costs is storage space, especially in more expensive urban areas. Therefore, silos simultaneously function as transport unit *and* temporary storage space—smart mobile warehouses. This way a silo at a constructions site can be transformed into a temporary material storage. This allows the material storage to be pushed into the major urban areas without incurring the associated costs. Besides total costs, the system evaluates these strategies based on performance indicators such as the number of silos, trucks in use, driving distances as well as load factors. Apart from hard economic aspects, soft factors such as employee and customer satisfaction as well as sustainability initiatives can be pursued.

Future research will be multi-faceted: For the improved quality and efficiency of the decision-making and planning processes, we want to extend our lightweight digital twin by including more descriptive data in the system. First promising approaches include the type and scope of the construction site, the condition of the access roads as well as price developments in transport services and building materials. A challenge of this use case remains the uncertainty in the various embedded processes. Going forward, the company seeks to leverage state-of-the-art predictive analytics to forecast daily processing quantity of individual customers, incoming orders, price developments, and traffic conditions. Network effects across plants and products increase the savings potential in transport costs the further the new logistics system is introduced.

In addition to the internal scalability of the approach, the lessons learnt from this project can be applied outside of the construction industry. Tanker trucks and bulk silos are widely used in other industries such as food, agriculture or plastics processing. Similarly, we want to evaluate new ways of transport such as electric trucks in urban areas or the functionality of our regional hubs. Finally, we want to investigate the interplay with different service level agreements and their robustness in critical situations as well as the impact of IoT-driven process transformations on customer relationships.

CRediT author statement

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