Using simulation to reshape the maintenance systems of caster segments

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Abstract: The maintenance of steel mills has a relevant impact on costs and productivity of steel industry. According to the traditional approach, one crew per shift takes care of the maintenance of key components of the slab caster with very limited process control, productivity and long lead-times. This paper introduces a new approach that makes each component move along a line where specific attention has to be paid to shared resources. The methodological approach is based on simulation, which has been applied to a real-life case study, represented by a leading Indian steel mill. Simulation is exploited, first, to point out the effect of the concurrent requirement of resources, demonstrating that a static sizing can lead to wrong designs, then, to properly consider the variance of execution times. Results show that caster maintenance arranged in a line designed according to the proposed methodology remarkably contributes to speed up the maintenance process.

Keywords: simulation; maintenance; steel mills; flow line.

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1 Introduction

The maintenance of steel mills has a relevant impact on costs and productivity and it is particularly significant nowadays since the steel industry is plagued by excess capacity, which has triggered – almost so far – cost-cutting plans and productivity improvement actions. Besides, the aging of steel mills makes steelmakers face important cost-related threats connected to:

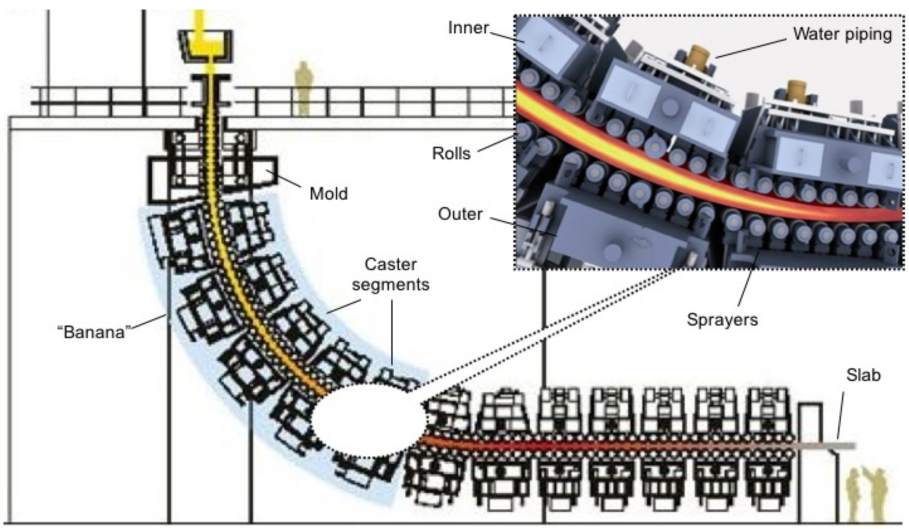
1 increased maintenance and repair costs

2 reduced productivity (Elliott et al., 2014).

In particular, caster segments – the pivotal components of the slab caster – have to be maintained on a regular basis to ensure steel quality.

Caster segments allow for solidifying the slab of liquid steel exiting the mould (see Figure 1) and they give the desired thickness to the final slab. Each segment is composed of an upper element (called inner) and a lower element (called outer) that are placed one over the other one. Both of them are provided with a set of rolls: the slab is milled by passing between the two sets of rolls, which are getting closer and closer as the segment approaches the end of the so-called banana. Beside the rolls, a segment is composed of many more elements: the crossbar (it connects inner and outer), the oil (needed to grease the segment elements) and water piping (to cool the steel slab passing through the segment), the corresponding sprayers, etc.

Figure 1 Typical layout of a slab caster where slab caster segments are highlighted (see online version for colours)



Caster segments are maintained periodically. When a segment needs maintenance it is replaced by another one in order not to stop the mill. The maintenance of caster segments – heavy (about 70 tons each), bulky and expensive (about 2 million $ each) – has a deep impact on steel mills costs. The longer and the more variable the maintenance time (downtime) the higher the number of segments needed to replace the ones under maintenance and to protect against the risk of casters failure, so the higher the operative working capital and the required storage room.

However, according to the traditional approach, just one crew per shift maintains each segment: the operators of the crew completely disassemble each segment one by one and assemble it again with new or renewed elements. All these activities are carried out in the area of the repair shop where the segment has been moved. Once they have repaired the segment, they go to another area of the repair shop where another segment to be maintained has been (randomly) placed.

This way of doing [known as fixed position layout (Chase et al., 2006)] appears to be relatively weak from several viewpoints. First, just one crew has to maintain an entire segment, which requires the operators to be skilled in all the phases (usually more than 50) needed to repair a segment. Second, process control is very limited: the only way to get a clear picture of the work progress lies in speaking directly to the operators. Third, performance indexes such as productivity, lead-time, and mean time between maintenance (failure) hit very low levels.

Recently, Ormis (an Italian company, see http://www.ormis.it), has developed a new approach to repair caster segments in line, where each segment moves along a (disassembly and assembly) line through a so-called transfer car, i.e., a motor-provided car moving on tracks, *ad hoc* designed. In a similar way as in the traditional manufacturing and/or assembly lines, each station of the maintenance line is devoted to a reduced set of activities, performed by a crew of operators, which is routinely assigned to that station according to the shift schedule.

The pace of the line is given and once the pre-defined time allowance has elapsed, all the transfer cars move forward. This leads to a well-defined maintenance process, and to a quick visual control of the work in progress. Besides, both the work content and the required skills are much lower than in the case of fixed position layout arrangement. Finally, in terms of performance, system throughput is expected to be improved (Kanaganayagam et al., 2015) and lead-time lower than under fixed position layout arrangement (Chase et al., 2006). However, the new approach described above, might be effective if the maintenance line is properly designed.

The problem of designing a maintenance line for caster segments can be modelled as a general problem of assembly line design (ALD), since the maintenance of a caster segment consists of disassembling and assembling. Besides, when considering steel mills, specific attention has to be paid to shared resources (Rossi et al., 2017a, 2017b). Most resources are expensive and bulky, and money and space requirements push to share them among different working stations. In addition, even though they are not very expensive, several working stations require an overhead crane and overhead cranes cannot over pass each other. Hence, beside money-related issues, shared resources have a pivotal importance in shaping caster segments maintenance lines.

Notwithstanding the relevance of the recent works on ALD (e.g., Michalos et al., 2015), the gap highlighted between the requirements of real-life configuration problems and the status of research (Boysen et al., 2008; Al Geddawy and El Maraghy, 2010) has not been filled yet. Moreover, despite the above discussed implication of costly resources in maintenance the literature review performed by Alrabghi and Tiwari (2015) shows that maintenance resources have been seldom modelled and they are normally considered always available.

Thus, the need for a new method to design caster segments maintenance lines, which is able to take into account shared resources, emerges. Simulation is perceived as an effective means for the analysis and optimisation of manufacturing systems (El-Khalil, 2013), appraise investments (Pozzi et al., 2015) and, in particular, according to Battaïa and Dolgui (2013), simulation is a powerful tool to evaluate the dynamic behaviour of the line. However, simulation has not been effectively exploited yet to solve the issue of shared resource in ALD-like problems despite it is the most appropriate tool to take into account several concurrent entities aiming to chase the same resources (Cigolini et al., 2011).

Therefore, the research question underlying the present research is how to design a maintenance line taking into account shared resources. In order the tackle this research issue a method based on simulation has been developed. The new method has been tested on a real-life case study, provided by a leading Indian steel mill willing to arrange the bays of its repair shop devoted to segments maintenance in line so to speed up the maintenance process.

The remainder of the paper is arranged as follows: Section 2 reviews the current methods to ALD and it is focused also on the use of simulation in maintenance and their limitations. The review has the aim to better introducing the need for a method able to support the line detailed design conceived by Ormis. Section 3 describes the new two-phase method, which combines lean principles and simulation. Section 4 presents the industrial environment, the application of the new method to a real-life case study and discusses the results of the implementation. Finally, Section 5 draws some conclusions and outlines future research paths.

2 Background

ALD comprises several problems (Michalos et al., 2015), including assembly line balancing (ALB) and layout determination (Boysen et al., 2007; Rekiek et al., 2002).

A plethora of models has been developed to solve the simple ALB problem, as discussed in the review by Baybars (1986) and by more recent reviews (Lusa, 2008). Later, Salveson (1955) developed the first mathematical formulation of ALB problems, while a number of models are devoted to the general ALB problem, as discussed in Becker and Scholl (2006). In general terms, ALD-related problems are difficult to be solved, being NP-hard (Boysen et al., 2007): various methods have been proposed (Rekiek et al., 2002; Boysen et al., 2008), ranging from analytical models (e.g., Caridi et al., 2006), linear and integer programming, neural networks and genetic algorithms (e.g., Rekiek and Delchambre, 2006; Tiacci, 2015; Araujo et al., 2015), to intelligent search algorithms (Michalos et al., 2015). Differently, Cannas et al. (2018, 2016) apply lean management principles to solve ALB problems.

Some methods that combine several techniques together provide interesting results. Liu and Chen (2002) proposed a two-stage method. In the former stage, they combine a multiple objective mixed-integer zero-one programming model with an interactive procedure, to simultaneously minimise workstation cycle time and the number of workstations, while satisfying the required total operation cost. In the latter stage, a visual interactive modelling system and the associated human-machine interface are built, to evaluate feasible solutions. Later, Özdemir and Ayağ (2011) proposed to integrate a branch-and-bound algorithm with analytic hierarchic process (AHP), to define both the allocation of different activities to workstations and the equipment.

Tiacci (2012, 2015) combine different techniques and simulation (e.g., genetic algorithms) for designing assembly lines. The models help simulate different arrangements in a quicker way than algorithms and procedures, by receiving as inputs the task times, the line configuration and the sequence of models entering the line. Notwithstanding the benefits – in terms of reduced computational time – got by this simulator, it still overlooks shared resources, a struggling real life issue. The same limitation is found in the works by Zupan and Herakovic (2015), Michalos et al. (2015, 2012), Cortés et al. (2010) and Corominas et al. (2011). All these papers do not consider shared resources, since as already observed by Boysen et al. (2007), they hypothesise all stations are equally equipped and if several activities need the same resources, the activities are combined into the same station. These models cannot be used in the case study reported here in that the tasks requiring the same resources cannot be combined in a unique station. Notwithstanding the increase in cost of equipment is seen as a drawback, the review by Lusa (2008) on multiple or parallel assembly lines highlights that no consideration of equipment sharing is provided by the revised works. Moreover, in the case study reported here there is a limit on the number of resources that can fit the maintenance bay. For example, each bay is usually equipped with no more than two over-head cranes, typically working in two different areas of the bay (since they cannot over pass each other), while the over-head crane is requested at least in five positions along the maintenance line. Handling different tasks requiring the same resources or equipment is a problem seldom treated by a limited number of studies (Boysen et al., 2007), mainly by assigning all the tasks to the same station and by considering costs and benefits of increasing the number of resources at that station. However, this approach does not fit the case of the overhead cranes reported above.

Simulation-based approaches allow to take into account the availability of all the resources required by two or more process phases. Indeed, simulation is popular to support the study of complex systems (Cigolini et al., 2011) and it exhibits various strengths over the practice of experimenting on real systems: lower costs and time for running experiments, repeatability, and safety (see, e.g., Cigolini and Rossi, 2004). As highlighted by the review of literature between 2000 and 2014 by Alrabghi and Tiwari (2015) simulation has been widely applied to study maintenance problems, it appears to be still developing for maintenance (Alrabghi and Tiwari, 2016). Some attempts have been done to use simulation in maintenance, e.g., (Alrabghi and Tiwari, 2016; Razavi et al., 2015; Lei et al., 2010), however it should be noted that they are not able to consider shared resources: Razavi et al. (2015) do not model how resources are used, Lei et al. (2010) take maintenance resources as input of the model.

3 Proposed method

The new method introduced here is oriented at properly configuring the maintenance line of caster segments, given the need to manage shared resources.

The new method is composed of a static phase providing a baseline for the dynamic one. The line is firstly designed in a static way, according to the lean principles. In this phase, the problem of shared resources is not considered. Then, the output of the former phase (i.e., the static configuration) is used as input of a discrete event simulator, to assess line performance when shared resources are considered. By doing so, the need to increase the number of some shared resources or to re-arrange the line emerges, thus leading to the final configuration of the line. The static design of the line is obtained through four steps, briefly summarised below.

3.1 Maintenance cycle analysis

The maintenance process has to be analysed. This requires the identification of the activities performed, the sequence of activities and the activities that are to be completed before starting each activity, the mean processing time of each activity i ($\overline{PT_i}$) along with its standard deviation (σ_i), and the resources required by each activity.

3.2 Definition of the maintenance process archetype

To reduce the complexity of the static phase, a maintenance process archetype is defined, starting from all the feasible options of maintenance processes. In this way, the next steps of the static phase are then performed on the maintenance process archetype.

The maintenance process archetype is the maintenance process of the most complex caster segment, i.e., the one that requires the longest time to carry out the phases. The cycle time (CT_i) to be considered for each phase of the maintenance process archetype is computed, in line with six-sigma theory (Montgomery and Runger, 2010), according to (1):

$$CT_i = \overline{PT_i} + 1.96\,\sigma_i \tag{1}$$

3.3 Calculation of target takt time

A target monthly throughput rate (TH) of the maintenance line has to be defined. Based on this, the target *takt* time (TT) of the line is defined, based on the number of hours in a month (NH) according to (2):

$$TT = NH/TH \tag{2}$$

3.4 Calculation of the number of stations and allocation of the maintenance activities

The number of stations in the line has to be picked between two bounds, according to (3):

$$\sum_{i=1}^{N} \frac{CT_i}{TT} \leq Number\ of\ \ stations \leq N \tag{3}$$

where N is the number of number of activities.

A number of stations equal to the lower bound is feasible only when each activity can be split in any number of ways, which is not commonplace in many industrial environments. Therefore, the number of stations can be assumed greater than the lower bound. The stations are then created by grouping n consecutive activities and assuming that there is no technological constraint preventing from performing in the same station two consecutive activities. So, for each station j, equation (4) is fulfilled:

$$Process\ Time_j = \sum_{i}^{n} CT_i \leq TT \tag{4}$$

Therefore, the output of the static phase is the number of stations of the line and the activities allocated to each station.

3.5 The dynamic phase

Based on the results above, the dynamic phase checks whether the line configuration identified through the static phase provides the expected performance in terms of throughput rate even when shared resources are taken into account. Otherwise, simulation is used to calculate how to increase the number of shared resources to hit target performance or to define a new arrangement of the line (a different number of stations given by a different way of grouping together consecutive activities).

The simulation-based dynamic phase is grounded on simulation model development process (SMDP, see Manuj et al., 2009), already effectively applied in Cigolini et al. (2014). SMDP involves eight steps (the first two steps derived from the static phase):

1 formulate problem
2 specify independent and dependent variables
3 develop and validate logical model
4 collect data
5 develop and verify computer-based model
6 validate the model
7 perform simulations
8 analyse and document results.

Focusing on data collection, the number of simulation replications, length and warm up period to account for the variability arising from the processes, we refer to Robinson (2004). According to his work, in case of a non-terminating simulation, i.e., simulation that does not have a natural end point, as a production facility that aims to determine its throughput capability is, the length of a simulation run needs to be determined by the model user and replications are not needed.

Petri nets (see, e.g., Pero et al., 2010) are suggested to build the logical model from which the simulation one is derived. Actually, Petri nets are probably the most helpful formalism to develop the logical model of manufacturing systems, in order to highlight different entities aiming to chase the same resource (Ezpeleta et al., 1995). Data required in the fourth step is collected in the first step of the static phase: it refers to mean and standard deviation of the process time of each activity and segment type. Consistently with the typical manufacturing context represented by assembly lines, a discrete-event simulation software package (e.g., Enterprise Dynamics®) is suggested to develop the computer-based model. Additionally, it helps automatically get a 3D animation of the model, which shows practitioners how their maintenance system is modelled. In this way, they can easily validate it.

4 Case study

The test-bed for the new model introduced here has been provided by the repair shop of a leading integrated steel producer. The plant capacity allows to produce 10 million tons of steel per year and it is the highest-productivity steel plant in India, with a yearly throughput rate higher than 800 tons per capita. The repair shop has pivotal importance in determining plant productivity in that it maintains all the items required to perform continuous casting (see Figure 1), including the segments. The target performance of the repair shop accounts for 30 segments repaired per month and hereinafter it is referred to as the target monthly throughput rate.

The application of the two-stage method (described in Section 3) combines a static sizing of the maintenance line (according to lean principles) with its testing via simulation experiments. The static sizing allows to find the line arrangement in terms of number of stations, allocation of maintenance activities to line stations and number of resources. Simulation aims at checking the outcome of the static analysis and at confirming it or at defining the best configuration to hit the target monthly throughput rate.

4.1 The static phase

In the first step of the static sizing, the segments maintenance cycle is analysed in terms of activities it is composed of, time needed for each activity and resources required. For each segment type, from the Ormis historical data and from time measurements in field, the best of fit cycle times distributions have been derived and the normal distribution results to be the one that best fits the available data. Due to confidentiality reasons, Ormis did not allow to report neither the historical and gathered data nor the detail of the distributions mean value and standard deviation.

The second step of the static sizing is to define the maintenance cycle to be considered. There are different segments to be maintained, therefore there are different maintenance cycles in terms of cycle time of each activity. However, in the static phase, an archetype of caster segment maintenance cycle can be built. In this cycle the time to complete each activities is the longest one among the times characterising the maintenance cycles of the real caster segments. In particular, the six-sigma theory is applied (Montgomery and Runger, 2010): the cycle time of each activity is given by equation (1) so to ensure that the probability the corresponding activity is completed by the cycle time accounts for 95%. Both the average cycle time and its standard deviation refer to the segment typology requiring the longest processing time. Table 1 shows the output of the second step. For the sake of clarity, some activities to be performed both on the inner and on the outer are conducted at the same time in parallel stations (Table 1 can be used to compute also the work content related to the maintenance cycle archetype, by multiplying the number of involved operators per crew *times* the cycle time of each activity).

In the third step, the maintenance *takt* time is calculated starting from the target monthly throughput rate (30 segments/month) and from the working hours per month. Since the repair shop maintains the items required to perform continuous casting (operating 24 hours per day, 365 days per year), the repair shop is supposed to work continuously as well. Therefore, (5) and (6) give the working hours per month and the line *takt* time respectively.

$$NH = 24[hours/day] \times 30[days/month] = 720\,hours/month \tag{5}$$

$$TT = 720[hours/month]/30[segments/month] = 24\,hours/segments \tag{6}$$

Table 1 The archetype of segments maintenance cycle

Activity	*Description*	*Cycle time [hours]*	*Operators*	*Resources*
1	Segment receiving from the steel plant	2.5	2	Overhead crane
2	Job order creation and documents printing	0.6	1	
3	Washing and clearing	10.0	2	Cleaning plant
4	First visual check	1.3	1	
5	Wedges and nuts disassembly	2.5	3	Jib crane
6	Upper frame disassembly (cross bar)	3.3	3	Jib crane
7	Pipes disconnection	3.3	3	
8	Pinch-roll disassembly	5.0	2	Jib crane
9	Inner overturning	3.3	3	Tilter
10	Lower rolls supports unscrewing (inner)	5.0	3	Pit
11	Lower rolls supports unscrewing (outer)	5.0	3	
12	Inner loading onto the transfer-car	1.7	3	Tilter
13	Roll-support base distance measurement	2.0	2	Overhead crane
14	Rotating joints disconnection	2.7	3	
15	Idler-rollers disassembly	6.7	3	Jib crane
16	Plates supporting rolls disassembly	5.0	3	
17	Rolls base support cleaning + general cleaning	6.7	3	Jib crane pit
18	Rolls support check	3.3	3	
19	Roll – plate distance measurement	3.8	2	
20	Sprayer disassembly	3.3	3	
21	Grease piping disassembly	3.3	3	
22	Painting	8.3	3	
23	Plates assembly (to close water holes)	3.3	3	
24	Water sealing check	3.3	3	
25	Leaks welding	12.5	2	
26	Grease piping assembly	16.7	3	
27	Idler-rollers assembly	6.7	3	
28	Pinch-roll and cylinder assembly	7.5	2	

Table 1 The archetype of segments maintenance cycle (continued)

Activity	*Description*	*Cycle time [hours]*	*Operators*	*Resources*
29	Sprayers assembly	3.3	3	Jib crane
30	Roll-support base distance measurement	2.0	2	
31	Rotating joints disconnection	2.7	3	
32	Idler-rollers disassembly	6.7	3	Jib crane pit
33	Plates supporting rolls disassembly	5.0	3	
34	Rolls base support cleaning + general cleaning	6.7	3	
35	Sprayer disassembly	3.3	3	
36	Grease piping disassembly	3.3	3	
37	Painting	8.3	3	
38	Rolls support check	2.5	3	
39	Roll – plate distance measurement	5.0	2	
40	Plates assembly (to close water holes)	3.3	3	
41	Water sealing check	3.3	3	
42	Leaks welding	12.5	2	
43	Grease piping disassembly	16.7	3	
44	Idler-rollers assembly	6.7	3	
45	Sprayers assembly	3.3	3	
46	Inner lift and overturning	5.0	2	Jib crane pit
47	Inner positioning on outer within the tie rod	3.3	3	
48	Cylinders assembly on the tie rod	5.0	3	Over-head crane tilter
49	Wedges or nuts tightening	3.3	3	Overhead crane
50	Oil pipes connection	10.0	2	Overhead crane
51	Water pipes connection	10.0	2	Jib crane
52	Rotating joints connection	6.7	3	
53	Leakage test	6.0	2	
54	Internal rolls gap oleo-dynamic measurement	10.0	2	
55	Sprayer check	6.0	2	

Equation (6) means that every 24 hours the line has to complete the maintenance of a segment. Indeed, the line *takt* time both identifies the time fence between two consecutive items completed, and it equals to the amount of time spent by the segment at each station.

Once the line *takt* time has been defined, the number of stations of the line is identified and the maintenance activities are allocated to the stations. According to equation (3), two bounds are set: the number of activities (upper bound) is given by the maintenance cycle analysis (see Table 1) and it equals to 55. The lower bound is calculated by considering the cycle time of each activity and the *takt* time, as defined above. In particular, equation (7) gives the lower bound:

$$INT\left(\sum_{i=1}^{N}\frac{CT_i}{TT}+0.5\right)=INT\left(285.1\,[h]/24\,[h/segment]+0.5\right)=12\,[stations] \quad (7)$$

Hence, the number of stations ranges between 12 and 55.

The maintenance cycle archetype and equation (4) help to group consecutive activities. According to Table 2, the number of stations is 15 and the line *takt* time TT is about 23 hours. Notice that static sizing overlooks the concurrent requirement of resources.

Once the static stage of the proposed approach is completed, i.e., a static line configuration has been defined, the discrete event simulator assesses the dynamic performance of the identified line configuration by taking into account the resources requested by different stations. The dynamic phase is detailed in the following paragraph.

Table 2 Number of stations and line *takt* time

#	*Station*	*Activity*	*Description*	*Cycle time [hours]*
1	1	1	Segment receiving from the steel plant	20.2 h
		2	Job order creation and documents printing	
		3	Washing and clearing	
		4	First visual check	
		5	Wedges and nuts disassembly	
		6	Upper frame disassembly (cross bar)	
2	2	7	Pipes disconnection	23.3
		8	Pinch-roll disassembly	
		9	Inner overturning	
		10	Lower rolls supports unscrewing (inner)	
		11	Lower rolls supports unscrewing (outer)	
		12	Inner loading onto the transfer-car	
3	3 inner	13	Roll – support base distance measurement	23.0
		14	Rotating joints disconnection	
		15	Idler-rollers disassembly	
		16	Plates supporting rolls disassembly	
		17	Rolls base support cleaning + general cleaning	
4	4 inner	18	Rolls support check	22.1
		19	Distance between roll and plate measurement	
		20	Sprayer disassembly	
		21	Grease piping disassembly	
		22	Painting	

Table 2 Number of stations and line *takt* time (continued)

#	*Station*	*Activity*	*Description*	*Cycle time [hours]*
5	5 inner	23	Plates assembly (to close water holes)	19.2
		24	Water sealing check	
		25	Leaks welding	
6	6 inner	26	Grease piping assembly	23.3
		27	Idler-rollers assembly	
7	7 inner	28	Pinch-roll and cylinder assembly	15.8
		29	Sprayers assembly	
		46	Inner lift and overturning	
8	3 outer	30	Roll – support base distance measurement	23.0
		31	Rotating joints disconnection	
		32	Idler-rollers disassembly	
		33	Plates supporting rolls disassembly	
		34	Rolls base support cleaning + general cleaning	
9	4 outer	35	Sprayer disassembly	19.2
		36	Grease piping disassembly	
		37	Painting	
		38	Rolls support check	
		39	Distance between roll and plate measurement	
10	5 outer	40	Plates assembly (to close water holes)	19.2
		41	Water sealing check	
		42	Leaks welding	
11	6 outer	43	Grease piping disassembly	16.7
12	7 outer	44	Idler-rollers assembly	10.0
		45	Sprayers assembly	
13	8	47	Inner positioning on outer within the tie rod	21.7
		48	Cylinders assembly on the tie rod	
		49	Wedges or nuts tightening	
		50	Oil pipes connection	
14	9	51	Water pipes connection	16.7
		52	Rotating joints connection	
15	10	53	Leakage test	22.0
		54	Internal rolls gap oleo-dynamic measurement	
		55	Sprayer check	

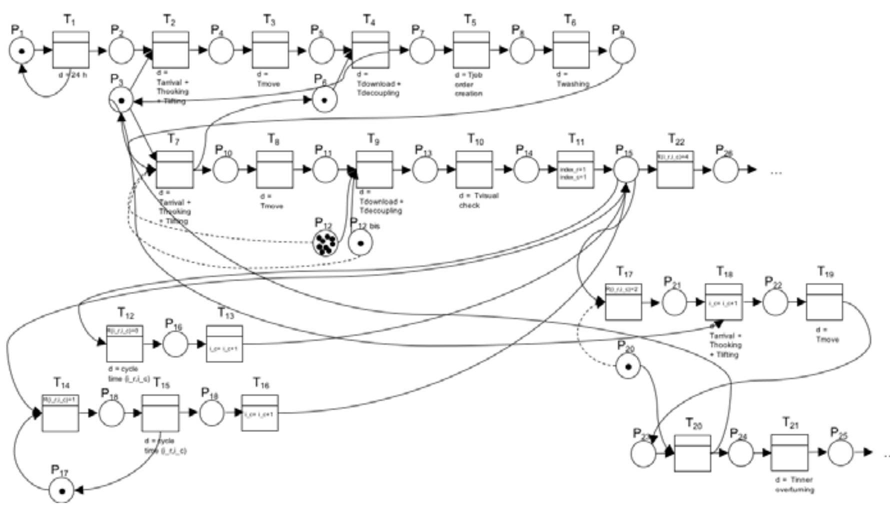
4.2 The dynamic phase

The dynamic phase is performed according to the SMDP approach. The first step requires the problem formulation. With reference to the above described context, the goal of the simulation study lies in making the (dis)assembly line reach the monthly-expected throughput of 30 segments (which corresponds to 24-hour line *takt* time), by performing the maintenance process according to the maintenance cycle reported in the first two columns of Table 1.

In the second step of the dynamic phase, independent and dependent variables are defined. The former ones are given by the number of resources (tilters, transfer cars, jib cranes) involved in the conduction of the maintenance activities and by the line arrangement (i.e., the number of stations). Process lead-time and *takt* time (TT) are set as dependent variables, since they result from the available resources and from line configuration. The so-called line flow time (i.e., the time each segment takes to go through the line) is a dependent variable, set as a control one.

As third step of the approach, the Petri net representing the maintenance line (see Reisig and Rozenberg, 1998) is developed and checked to test whether the line was modelled appropriately. To identify all the model components, their own dynamics and the general functioning of the line, Ormis personnel was involved. Besides, Ormis personnel gave a relevant contribution of experience along the validation process. Figure 2 depicts an extract of the Petri net of the maintenance process. In particular, the extract represents the process from the segment arrival up to the completion of the maintenance activities performed in line position 2 (identified the place P_{26}, representing the outer, and the place P_{25}, representing the inner). The shared resources in the line are modelled in places P_3 (overhead crane), P_6 (cleaning plant), P_{12} (transfer cars), P_{17} (jib crane), P_{20} (tilter).

Figure 2 Extract of the Petri net: from the segment arrival up to the completion of the maintenance activities performed in line position 2



Within the fourth step, data input to the model was the mean $(\overline{PT_i})$ and standard deviation (σ_i) of each activity's processing time of for each segment typology (already collected in the first step of the static phase). A typical sequence of segments of different types to be maintained has been added. Within the simulation model, mean values and standard deviations are to be used to parameterise the normal distributions used to pick the random values of the processing times (here it is worth to recall that, as stated above, due to confidentiality reasons, Ormis did not allow to report those mean values and standard deviations).

Finally, the Petri net resulting from the third step was translated into a simulation model through Enterprise Dynamics 9.0 (see Figure 3). Since the developed model simulates a future segments maintenance line, i.e., at the time the simulation model was developed the maintenance line did not exist, according to Greasley (2008), the model validation was undertaken by means of the 3D animation automatically built by Enterprise Dynamics 9.0. The 3D animation was shown to Ormis' technicians. They confirmed that the functioning of the model was coherent with the way of working of the conceived caster segment maintenance line. Of course, when performing the ED simulation replications, a dependent variable is registered and used as control variable.

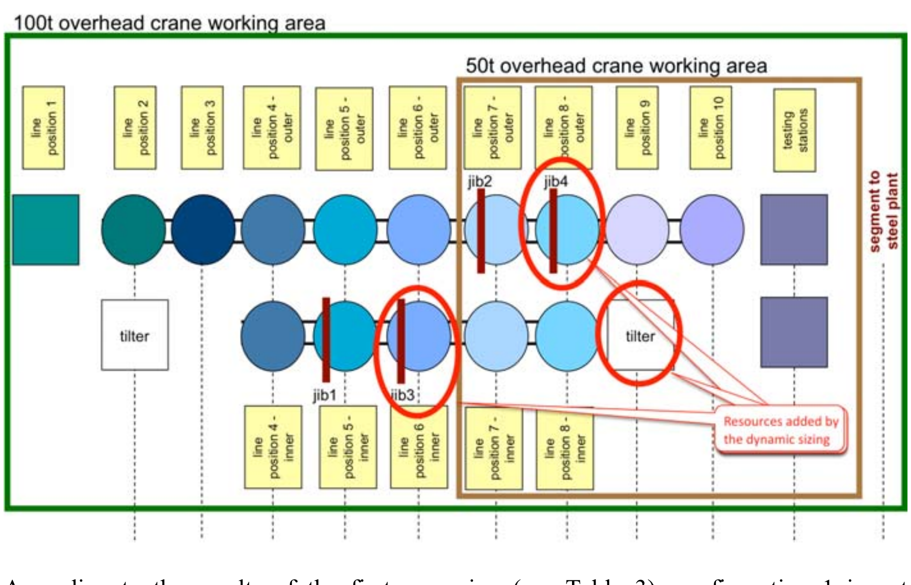
Figure 3 3D animation of the enterprise dynamics simulation model (see online version for colours)

According to Cigolini et al. (2014), once the simulation model is built and debugged, simulation runs can be executed and results are collected, carrying out the sixth step. Two simulation campaigns have been performed with different aims. The objective of the first campaign is in pointing out the sole effect of the concurrent requirement of resources by different workstations, without taking into account the variance of execution times. The second campaign aims at studying the effect of the variance of execution times on an identified configuration, by presenting the performance of the line when time variability is also considered.

The first one performs the dynamic phase considering deterministic activities completion times set equal to $\overline{PT_i} + 1.96\,\sigma_i$, i.e., to simulate the case where the number of segments that would require more than such amount of time to be completed corresponds to 2.5% of the number of segments to be maintained. The first simulation campaign was done with the aim of isolating the effect of resource sharing from variability in activities execution time, thus highlighting only the effect of concurrent requirement of resources. The output of such campaign is the configuration of the line that, considering the concurrent requirement of resources, allows the line to meet the requirements with a probability equal to 97.5%. Unfortunately, in the real-life Indian steel plant the length of the bay devoted to the segments maintenance physically limited the length of the maintenance line. Hence, increasing the number of stations of the line is more complex than merely increasing the number of shared resources. Therefore, an iterative approach has been applied to the experimental campaign, to test the maintenance line firstly under the configuration identified by the static stage and then by increasing one by one the shared resource with the highest saturation (the bottleneck) according to simulation results. If the increased number of shared re-sources does not allow hitting the targeted performance, experiments with a higher number of stations will be executed.

In the end, two configurations have been tested, i.e., configuration 1 and configuration 2. The former corresponds to the one identified by the static stage, parametrised by 13 transfer cars, one tilter, two jib cranes (one for the outer sub-line and one for the inner sub-line, as shown in Figure 4).

Figure 4 Dynamic vs. static sizing configuration (see online version for colours)



According to the results of the first campaign (see Table 3), configuration 1 is not suitable for further investigation. In fact, the monthly-expected throughput rate (i.e., 30 segments) is not met, completing the maintenance of either 19 or 20 segments per month, i.e., a segment gets out from the line every 37 hours instead of 24. Moreover, both tilters and cranes seem to be bottleneck resources, as their utilisation rates are higher than 95%.

For this reason, in configuration 2 the number of both available tilters and jib cranes has been increased.

Configuration 2 is parametrised by 13 transfer cars, two tilters and four jib cranes (two for the outer sub-line and two for the inner sub-line – see again Figure 3). Table 3 presents the performance indexes gathered for each scenario simulated in the first campaign: the maintenance process lead-time (the amount of time needed to complete the archetype cycle), the line flow time (the time the segment spends to go through the line) and the line takt time (the amount of time between the completion of two subsequent segments).

Table 3 Characteristics and performance indexes of scenario 1 and scenario 2 tested by the first simulation campaign

Scenario		*1*	*2*
Available resources			
Transfer cars	#	13	13
Tilters	#	1	2
Jib cranes	#	2	4
Performance indexes			
Maintenance lead time	[Days]	78.6	8.64
Line flow time	[Days]	9.5	7.84
Line takt time	[Hours]	37	24
Line throughput rate	[Segments/month]	19.5	30

The output of the first campaign confirms that the mere static sizing of the line overlooks the effect of concurrent requirement of resources. Indeed, according to Table 1, the tilter is involved in activities number 9, 12 and 48, performed by stations number 2 and 8, and to complete these activities 1.7 hours, 3.3 hours and 5 hours are respectively needed. Then, according to the static sizing, the saturation of the tilter should be about 42%, while, according to the dynamic sizing, the value hits 95%.

The second campaign thoroughly investigates the configuration that, according to the results obtained in the first simulation campaign of the dynamic sizing, meets the requirements, i.e., configuration 2. Ten independent one-year replications were executed. The simulation is run repeatedly and the performance indexes are recorded over each replication: for each maintained segment the lead time and flow time data are recorded and for each replication line takt time and throughput rate are evaluated. The number of replications rely on the graphical method described by Robinson (2004): as the cumulative mean data lines representing the performance indexes stabilise, no significant difference between mean performance indexes can be reported. As few replications could lead to an overestimate, even if the line becomes flat around a number of replications that is lower than ten, ten is a more conservative estimate of needed number of replication. Moreover, as the simulation of the maintenance process is a non-terminating one, a unique long run would have been valuable, but multiple samples are taken in order to obtain a better estimate of mean performance. The run length is set to one year to reflect the fact that the maintenance department plans annually for its operations. Since the line is considered to start with no segments under maintenance, a one-week warm-up period is considered, representing an amount of time sufficient to occupy all line positions that use shared resources (i.e., line position 9 performing activity 52, requiring the use of jib crane, is occupied from the 169-simulated hour) with 97.5% of probability. In all campaigns and replications, resources availability was assumed to be 100% and the model monthly-expected throughput rate of 30 segments (when shared resources are considered) was checked.

Table 4 presents the performance indexes gathered for configuration 2 simulated in the second campaign. First, the maintenance process lead-time (the amount of time needed to complete the archetype cycle) expressed by the calculated mean and standard deviation values. Second, the line flow time (the time the segment spends to go through the line) stated by the calculated mean and standard deviation values. Third, the line takt time (the amount of time passed between the completion of two consecutive segments).

Table 4 Performance indexes (mean and standard deviation values) of scenario 2 simulated in the second simulation campaign

Performance indexes		*Mean value (μ)*	*standard deviation (σ)*	*μ + 3 σ*
Maintenance lead time	[Days]	4.49	0.35	5.53
Line flow time	[Days]	4.49	0.35	5.53
Line takt time	[Hours]	24	-	-
Line throughput rate	[Segments/month]	30	-	-

4.3 Results

In the case study presented here, a traditional static sizing would have been used to design the caster segments maintenance line, thus overlooking the effects of shared resources. The new two-phase method combines a static sizing (line balancing based on lean theory) with a dynamic one (involving discrete event simulation).

It can set a baseline configuration, test its performance and, if the baseline is unable to reach the line expected throughput, identify the most proper line configuration.

Table 3 representing the output of the campaign that considers only the concurrent requirement of resource, highlights that 13 transfer cars, two tilters and four jib cranes are required to hit the targeted monthly throughput rate with a 97.5% probability. Moreover, the maintenance lead-time related to configuration 2 is lower than the one related to configuration 1. Hence, the number of caster segments to be kept as stock (to replace the ones under maintenance and to protect against casters failure) is lower as well in configuration 2.

Table 4 shows that the target monthly throughput (i.e., 30 segments) is reached, confirming that the output of the first campaign is sound. In addition, by considering activities times as normally distributed instead of crisp values, maintenance lead time and flow time are, on average, shorter than 5.53 days with a probability of 99.87%. Finally, equal values of flow time and maintenance lead time, meaning that the amount of time a segment needs to go through the line corresponds to the one needed to complete the maintenance archetype cycle, show that, on average, the segment starts maintenance activities as soon as arrived in the line, and waiting time is zero.

To determine the number of segments to be kept as stock according to scenario 2, a tool based on visual basic application (VBA) has been developed. This VBA-based tool receives as input:

1 the mean time between maintenances of each typology of segment

2 the time spent in operation by each segment

3 the maintenance lead time estimated via simulation.

The VBA allows to define:

1 when each segment should be disassembled from the continuous caster, and, as a consequence

2 how many segments (of the appropriate typology) are needed to run the continuous caster without stops.

The VBA-based tool highlighted that, for each of the four continuous casters the Indian mill is provided with, just 23 segments (15 working in the caster and 8 in maintenance/standing by) were required, while under the traditional (batch) maintenance system each continuous caster would need 25 segments (15 working in the caster and 10 in maintenance/standing by).

Table 5 Output of the VBA-based analysis considering one continuous caster

		Batch arrangement	*Line arrangement*
Total segments needed	#	25	23
Segments in the caster	#	15	15
Segments in maintenance/standing by	#	10	8
Operative working capital	M$	50	46

When the number of standing-by segments is reduced by two items, the operative working capital of the steel mill is reduced by about 16 million $. The case study also demonstrated that the line arrangement has a significant edge over the batch one since it leads to significant savings in terms of operative working capital and remarkably contributes to speed up the process until a 24-hour *takt* time was reached.

5 Discussion and conclusions

To find out the appropriate configuration of an assembly line a two-stage method has been developed starting from the need to help develop maintenance lines for the steel industry. The newly conceived method explicitly takes into account the case of several resources are shared, which is not commonplace. In fact, notwithstanding numerous works on ALD have been presented in literature, sparse or even not existent contributions can be found when it comes to propose models that specifically address the issue of sizing assembly lines where different stations compete for the same resources. Moreover, facing this issue is innovative when considering the steel industry that traditionally organises maintenance activities of key components (i.e., caster segments) in batch, and suffers of its impact on costs and productivity. To prove the effectiveness of this new method, it has been applied to the plant of an Indian leading integrated steel producer composed of a line with 15 stations (one washing machine, 13 transfer cars, one tester), two over-head cranes, two tilter and four jib cranes as shared resources. Results show that the new method allows complying with the desired throughput rate, accounting for 30 segments maintained per month.

In addition, the newly designed maintenance system allows to operate the four casters of the considered steel mill with 92 segments instead of 100 which would be otherwise required by the traditional fixed position layout, thus leading to 16 million $ saved in terms operative working capital.

The results above prove both the effectiveness of the newly conceived maintenance line for caster segments and the effectiveness of the two-stage method for sizing assembly lines with shared resources. Notice that the line configuration obtained via the static stage, alone – which comes from a line balancing methodology based on the lean theory – is totally unable to meet the targeted throughput rate. To do so, two more jib cranes (one for the inner and one for the outer sub-lines) are to be added, as suggested by the simulation study embedded in the dynamic stage. This in turn leads to conclude that simulation might represent a useful tool to size assembly lines, where several stations compete for the same resources.

This study proves also that current fixed position layout arrangement of the segments maintenance system is remarkably under-optimised. This is due to several reasons, related to:

1 the skills required to the maintenance operators

2 the limited control on the maintenance process

3 the reduced productivity, lead-time and time between maintenance (failure).

Here, a new concept of caster segments maintenance system has been developed: the segments are maintained in line, which requires them to be completely disassembled and assembled with new or renewed components.

Finally, an obvious future research path is related to the extension of the study to other industries that could benefit of the proper size of assembly lines characterised by shared re-sources, either considering their core activities or service activities, as maintenance. However, the purpose of applying the present methodology to other studies could be limited by the amount of time required to build a simulation model, known as a time-consuming activity. With the aim to overcome such limitation, the development of a simulation meta-model, allowing for automatically building a variety of assembly lines simulation models, independent of the corresponding industry, could help in improving the opportunity to properly size such assembly systems.

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