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LAYOUT AND MATERIAL FLOW OPTIMIZATION IN DIGITAL FACTORY

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Abstract
The ability to realize customized products, in particular for engineering-to-order companies, is a key factor in order to be competitive in modern market without incurring any additional cost and respecting customer lead time. In this ever-changing environment the layout optimization is a fundamental issue requirement, hence the development of a virtual layout, according to the Digital Factory concepts, can be very useful to identify and to solve potential problems during the planning phase, before realize it. The main aim of this paper is represented by the proposal of a layout reconfiguration and a technological solution for the parts feeding system of the industrial plant analysed in order to reduce the production lead times.

In the first phase, an overview of the Digital Factory applications is provided. In the second phase, after data analysis in an Italian manufacturing company, a simulation model has been designed and tested using Simio simulation software. Simulations results concerning production and queue times obtained from different orders have been compared with actual configuration data.

Research results indicate that the surveyed company has had an improvement in terms of reduction of waiting times and increase of customers satisfaction due to total production lead time reduction.
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Key Words: Digital Factory, Layout Optimization, Manufacturing and Simulation Model, 3D Simulation

1. INTRODUCTION

In the past customer demand was more stable and the companies less subject to foreign competition than today [1]. Indeed in modern manufacturing the demand for customization and high-mix is growing [2].

The time to market has been reduced; customers have more different requests and ask for high quality finished goods but also at low prices. This is the scenario of a new world in which factories had to work and fight to predominate over the other competitors.

In today's competitive global marketplace, the use of strategies to absorb fluctuations in demand, to develop and introduce new products in the production planning using existing facilities are seen as important competitive issues [3].

All these factors can be considered as responsible of a new kind of manufacturing systems, which are characterized by flexibility and reconfigurability [4]. An important issue concerns how much flexible the layout should be in order to face the possible future changes in product demand and product mix. Nowadays the choice of the right facility layout for firms is a real strategy. The improvement of flexibility has become increasingly important as a method to achieve competitive advantage in manufacturing companies [5-8]. Therefore this

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decision should be done carefully, only after an in-depth analysis of the detailed operational requirements of the firm they refer, including the layout of the plant.

The layout planning design is a complex activity involving the optimization of the positions of machines, transportation systems and workstations. Nowadays, the layout optimisation, as well as re-layout optimisation, has been made more efficient by using information technology tools, e.g. simulation software.

The use of simulation techniques for the design and optimisation of production processes and system is known as Digital Factory [9]. The Digital Factory includes both the products development, e.g. developing 3D models, and the production planning and systems. It is common practice to use digital product development tools in companies, and the scientific literature is full of published studies. However the focus of this paper is on the production planning aspect of Digital Factory concept. The Digital Factory concept allows designing, evaluating, monitoring and controlling the whole manufacturing system using the 3D simulation in order to create virtual 3D layout that represent the real facility. The development of a virtual layout can be very useful to identify and to solve potential problems during the planning phase, before realize the factory [10].

Potential problems could be related to the material flows and handling, fundamental key factors for the design of a functional system. According to Wy et al. [11] simulation can be used to analyse how system performance is affected by the layout configuration, the number and the type of material handling system used.

The 3D visualization allows representing aspects impossible to represent in a 2D way, e.g. the people and material flows in the factory layout.

Simulation tools are largely used to check the system behaviour before building it and invest in human resources, instruments, robotic systems or layout reconfiguration. Using this approach, firms can save large amounts of money.

This technology provides a big support for the decision-making process by means of complete representation of the manufacturing process as well as manufacturing layout, enabling them to inspect and walk around the rendered factory plant 3D model.

The paper explores one of the several aspects assessed by the Digital Factory implementation approach. In the Digital Factory concept, the virtual models are necessary in order to design and explore factories layout, using CAD 3D-factory models. According to Westkämper [12] simulation and 3D-visualisation are essential methods and tools for a proper implementation of Digital Factory.

In this paper a new layout configuration for the investigated manufacturing firm has been evaluated developing a 3D model. The object-oriented simulation software Simio Simulation has been used to simulate the new process layout in which different department are connected through a conveyor system, which impact many manufacturing parameters, i.e. set-up and run times, lots size, queue times and manufacturing cost. This software assists experts to evaluate the effects of this proposal and to obtain information about factors which influence lead time performances. Research results demonstrate that a small investment related to reconfiguration implies a high lead times reduction.

The remainder of this paper is organized in six sections: after this introduction, in the second section the framework is described; the methodology is analysed in the third section; the fourth section deals with problem definition; the simulation model results are reported and discussed in the fifth section; finally, conclusion and implications are in the sixth section.

2. FRAMEWORK

The Digital Factory approach is based on the integration of methods and tools to plan and test the product development and its related production process in the design phase [13].

Already in the 2000, Wörn et al. [14], introduce the Digital Factory concept and identify the several processes that this new innovative approach to factory automation integrates: product and production process development and optimisation, production facilities design and improvement, as well as simulation concerning production planning and control.

Some of the typical simulation applications [13] in the Digital Factory are:

1. Production control and simulation of production flow,
2. Line balancing of assembly processes,
3. Simulation of material handling systems,
4. Industrial robotics work cells,
5. Ergonomics evaluation through simulation of human resources,
6. Design, validation and optimisation of Digital Factory layout.

Depending on the particular goal of the simulation different tools and levels of detail are required.

As concern the *production flow planning and control*, mainly discrete event simulation is applied. The continuous interaction between factory planning and factory operation is required in order to implement and verify the operations planned in the virtual model in the real factory [15]. Using material flow simulation technology is possible calculate the buffers dimension as well as evaluate key performance indicators, e.g. total processing time or setup times minimization [16, 17].

Realize *an assembly line* able of producing the desired product is the main aim of every company [18]. The assembly line design in turn includes three problems, the layout configuration definition, the selection of the right equipment and the balancing of the assembly line [19]. The assembly line balancing consists in the assignment of operations to workstations in order to reduce the idle time satisfying precedence constraints [20].

In manufacturing systems the *materials handling* technology used is very important in order to reduce the cycle-time. Time spent for materials handling (raw materials and work in process) is considered waste. For this reason the feeding system should be designed more functional as possible and it depends on several factors, such as the lot size, the number of components and the distance between warehouses and assembly lines [21].

In the last years, the 3D simulation is largely employed also for *robotic work cells*, to verify the behaviour of robots in flexible manufacturing cells [22]. The simulation modelling of robots was born to analyse the interactions of robots with the other objects of the manufacturing cell, including robots, and to overcome the problem of possible collisions simulating the trajectories [23].

In recent years industrial plant safety focuses on human-factors engineering, also known as *ergonomics*, and main specifically on the study of designing equipment and devices that fits human bodies and cognitive abilities monitoring workers operating conditions. Also the scientific community is moving in this direction. Recent studies showed that the improvement of working conditions improves product quality and plant productivity [24-26]. A new methodological framework has been proposed in order to link assembly systems design and workplace ergonomics considerations optimizing both productivity and quality of workers workspace [27].

Finally there is the design, validation and optimisation of Digital Factory *layout*. As well as design and location of organizational facility, the industrial layout design is a critical aspect in order to maximize both the efficiency and the effectiveness of operations system [28]. For example, Discrete Event Simulation (DES) modelling of a digital manufacturing system can be employed to analyse the system's production performance, layout, ergonomics and robotics issues, through 3D motion simulation [12, 13].

Internal transportation costs minimization [29] is one of the most common criteria used for layout planning and design, as well as productivity maximization [30].

There are several scientific papers in literature focusing on facilities planning simulation [31-38]. The applications could be deal with the creation of a new factory or the improvement of an existing one. In the last case, e.g. the production capacity or the layout should be changed and optimised according to a new production programme. Therefore it is necessary to reduce the planning time [39] in order to be more responsive. As a result, it is necessary reduce the production planning phase, mainly related to facilities, analysing all the relevant data in order to understand potential savings and costs reductions.

The focus of this paper is on the optimisation of the materials flow improving the layout facility of the firm investigated.

For this paper the potential of the Digital Factory tool is very high. This accelerates the planning process by showing workflows, as well as logistics and production sequence simulation. The aim is to make a computer model of production plant in order to evaluate and improve production according to technical, logistical and commercial criteria.

3. METHODOLOGY

According to the Toyota Production System (TPS), and the more generic Lean Manufacturing principles, typically in a manufacturing system seven types of waste can be identified: high inventory levels, overproduction, empty running, delays, unnecessary processes, defects and materials handling. Many of these are caused by a non-functional layout. A well-designed layout minimizes the material-handling flow, transportation distances, and movement of people within the industry, making the manufacturing system more productive and efficient. The layout has to be designed in such a way that the products move between the various areas in the simplest way possible.

Generally the study of plant layout is made for the realization of a new product production or the improvement of an existing facility. Possible changes of products characteristics, customers demand, local regulation related to workers operating conditions (ergonomics) or environmental issues required a re-planning of the layout facility. In any case modelling and simulation techniques enable dynamic analysis to ensure that plant design problems and potential wastes are discovered before the company realize the plant.

The most used technique for the study of the layout, was introduced in 1973 by Richard Muther and it is called Systematic Layout Planning (SLP). It can be divided into three basic phases:

- careful and comprehensive data collection,
- evaluation of possible solutions and their performance,
- improvement and selection of the best solutions.

The methodological approach followed in this paper (schematically shown in Fig. 1) has been adopted by the framework proposed by Muther.

4. PROBLEM DEFINITION

The manufacturing company investigated operates in southern Italy. It produces six different type of insulating coatings in “engineering-to-order” environment. After an in-depth analysis, has been recognized that several aspects should be optimized in the factory layout in order to reduce lead-times and both material and resources flow. One of the main efficiency of the production process analysed is related to the time spent handling work in process between service stations. Currently the work in process is loaded in buffers next to each workplace. When the worker of the downstream work centre is available they are transported from one station to another without considering neither the batch size nor the production plan. Therefore the work aims to analyse the improvements obtainable from both layout re-design and the introduction of a belt-conveyors system in order to which ensures continuity to the production line, reducing the idle time and resources flow. This new scenario will be simulated using the simulation software Simio.

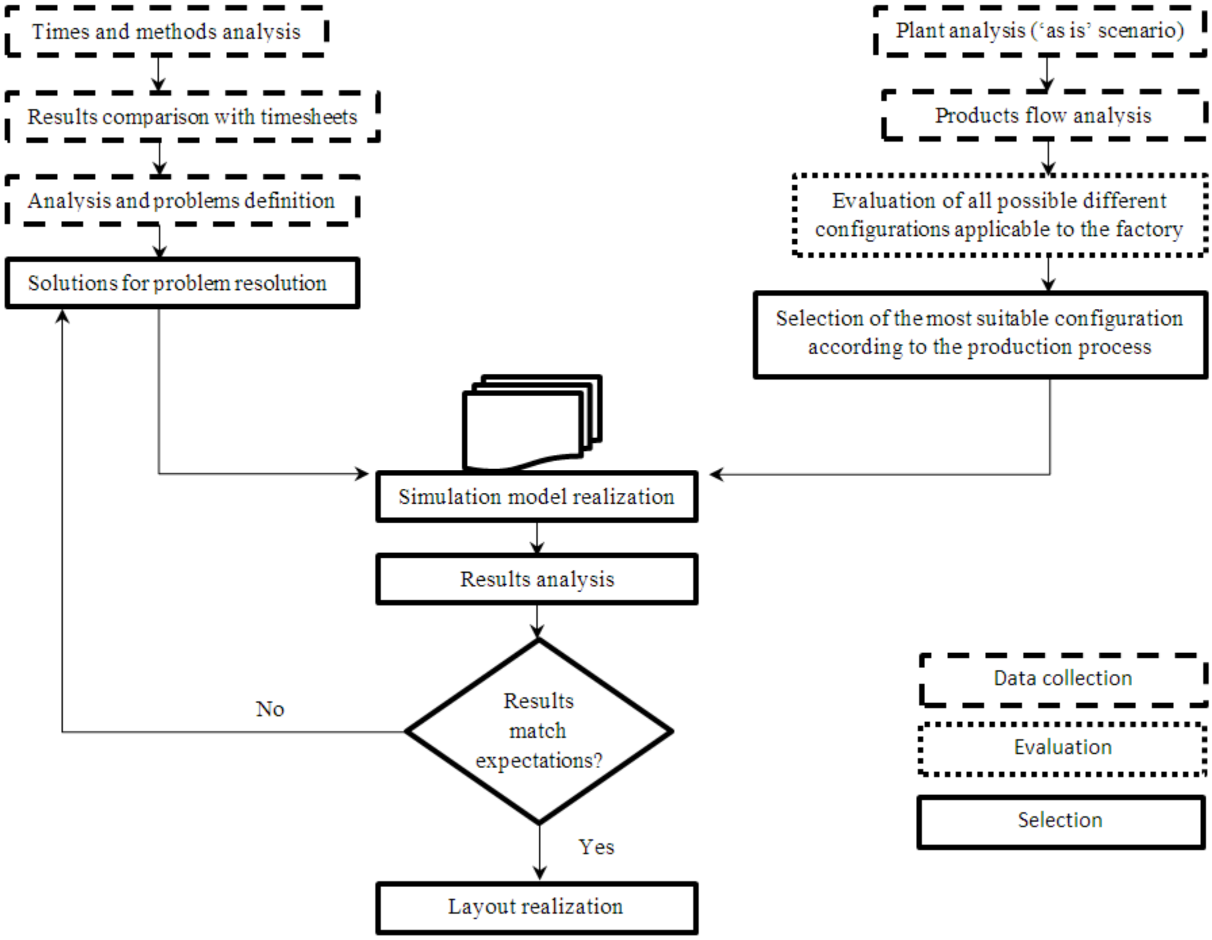


Figure 1: Flow-chart of the methodology.

4.1 Data collection: times and methods analysis

An accurate and direct in-depth analysis of the times and methods has been conducted by analysing the time required for each product in each work centre. The 3D model requires several essential inputs for the simulations, e.g. the entities, the workstation typology, the setup times, the processing times, the operations routing and so on.

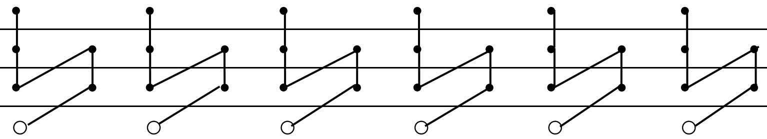
4.2 Selection of most suitable configuration

According to the production process, the industrial plant can be configured as a process layout. The production process is rather simple, not technologically advanced machines are required. Another simplifying aspect is that all the products follow the same processing cycle although the processing time required by each product results to be different. The first step is to analyse the processing cycle from a qualitative point of view (diagram of the operational process) of each product that has been represented in Table I.

The production process is rather simple. However, the processing times of the products are different. The processing times differences are related to the complexity of each component. The production process starts in the work centre W1. When the established lot size is reached, the lot passes in the second work centre. Actually the work in process materials handling is achieved thanks to an operator of the summit station that places the lot in the buffer of the downstream station. It is clear that this is a double waste of time: the operator inactivity due to material handling and the time spent waiting for the remaining lot in the bottom station. Since the workers check all the products, non-conformities, in terms of quality, are forthwith identified and corrected. This allows considering the absence of material scraps and rework processes.

Table I: Product flow diagram (Oi: Operations required; Pi: i^{th} product).

Pi		P1	P2	P3	P4	P5	P6
Materials Warehouses		▼	▼	▼	▼	▼	▼
Oi	O1						
	O2						
	O3						
Shipping Area							



In each case, the objective of the layout will be to have a progressive flow with a minimum of returns, and to have available consecutively the operations related to large flux intensity. The Hollier algorithm represented in Table II allows determining the right position of the machinery in order to make the route as linear as possible.

Table II: Elaboration of *from/to* chart (all data has been opportunely weighted and normalized).

	TO	1	2	3	**∑ From**	**∑ From / ∑ To**
FROM	1	0	0.5	0	0.5	∞
	2	0	0	0.5	0.5	0.5/0.75=0.66
	3	0	0.25	0	0.25	0.25/0.5=0.5
	∑ To	0	0.75	0.5	1.25	

Analysis shows that the optimum work station disposition of the units is 1-2-3. A hybrid “U” layout turns out to be particularly suitable for products that are on the production line; in each area there will be machines and tools to perform the same operations.

4.3 Software modelling and simulation

In the model developed the machines are disposed according to a hybrid layout as the products are different but follow the same cycle, so "being the differences" rather small it can be assumed a layout in which the machines are grouped by bringing in a single department all machining of the same type. It is also chosen to dispose the machinery in the shape of U.

In the Fig. 2 a 2D view of the plant is provided where the three manufacturing departments and the shipping area are cleat and appropriately highlighted.

This configuration is particularly suitable as it allows:

- closeness between workstations,
- flow continuity,
- increased communication, flexibility and control,
- reduction of the maximum queue during processing and idle time.

The objective to be achieved is the minimization of the cost due to materials handling.

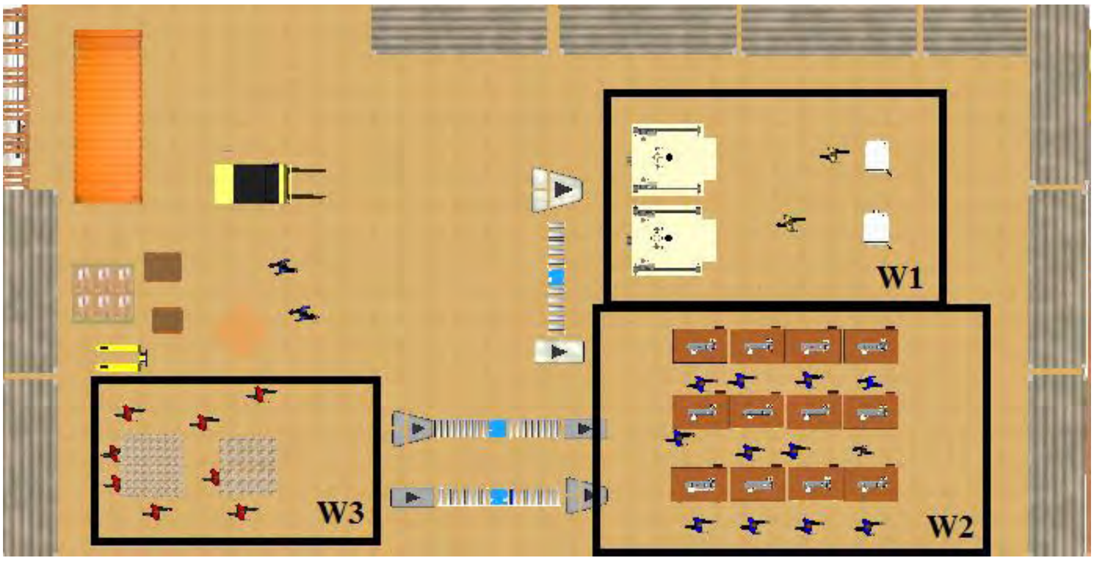


Figure 2: 2D-view of the layout designed through the simulation software
(W1: Work centre 1, W2: Work centre 2 and W3: Work centre 3).

The main aim of 3D simulation is establish if the layout reconfiguration and the conveyor system implementation in the manufacturing system analysed lead to an improvement in terms of performances as well as analyse the human-machines interactions. In this software, due to complete the simulation is necessary to insert several input data. The 3D model (Fig. 3) represents the manufacturing factory planned; it simulates the production process, the automated belt conveyors carrying the pieces from one station to the buffer of the work centre immediately downstream of the production cycle, the storage and shipping area.

Figure 3: 3D-view of simulation model.

5. SIMULATION MODEL RESULTS

In this section will be reported and analysed the results obtained from the eleven simulation runs. The data required to compare the results of the simulation and the real data are the following:

- $t_{p,i,j,k}$, which represents the effective processing time required by the product k for the operation i on machine j;
- $t_{s,i}$, time required to set the equipment and prepare the materials required to perform the operation i;
- $t_{q,i}$, waiting time of WIP before operation i.

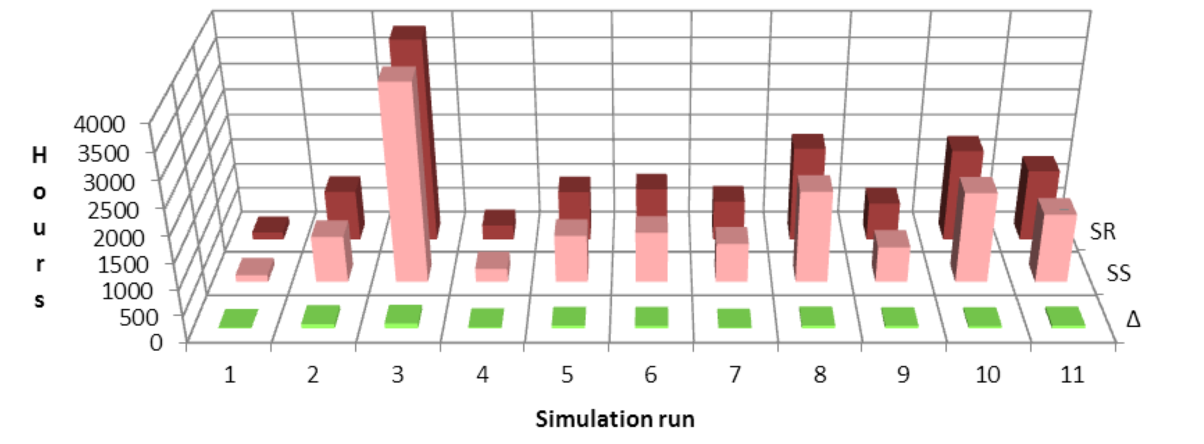
The tables III, IV and V summarize the results obtained by the simulation. The compared results, appropriately parameterized with respect to a k-factor, are described and discussed below.

After completion of the simulation model and insertion of the required data eleven simulation runs start. Different scenarios have been simulated, accordingly to the different company orders and the results have been compared with real data.

Table III summarizes the cumulative time spent by work in process in each work station and machine. On the other hand, Table IV reports a comparison between simulation results related to production times and real data. The last column contains the percentage value due to time reduction (ε_R).

Table V contains the comparison between real and simulated scenario. In all cases the firm obtains a time reduction that ranges from 8 to 1 %.

Finally Fig. 4 reports the total time required in 'as is' scenario (S_R), the total time required in the new scenario simulated (S_S) and the time savings expressed in hours.



	1	2	3	4	5	6	7	8	9	10	11
Δ	9	81	93	18	51	47	13	54	43	38	53
SS	135	899	3812	267	920	983	767	1783	698	1755	1340
SR	142	980	3904	285	971	1030	780	1837	742	1793	1393

Figure 4: Simulation results expressed as the total time required in 'as is' scenario (S_R), the total time required in the new scenario simulated (S_S) and the time savings (in hours).

The new system performances are definitely better than the real ones. In particular, the introduction of the conveyor system allows to reduce the waiting time spent for the batch being completed, the time spent by the operators for materials handling between the work centres. This time reduction results in a substantial total cost reduction for the company.

6. CONCLUSIONS AND IMPLICATIONS

Digital Factory approach provides a big support for the decision-making process by means of complete representation of the manufacturing process as well as manufacturing layout, enabling them to inspect and walk around the rendered factory plant 3D model.

Table III: Simulation outputs related to production time spent in each work station.

k / j	$t_{p,1,j,k}$			$t_{p,2,j,k}$ and $t_{p,4,j,k}$													$t_{p,3,j,k}$ and $t_{p,5,j,k}$									
	1	2	$\sum_j t_{p,1,j,k}$	1	2	3	4	5	6	7	8	9	10	11	12	$\sum_j t_{p,2,j,k} + \sum_j t_{p,4,j,k}$	1	2	3	4	5	6	7	8	$\sum_j t_{p,3,j,k} + \sum_j t_{p,5,j,k}$	$\sum_{i,j} t,p,i,j,k$
1	640	640	**1280**	180	155	201	170	158	167	206	187	192	180	-	-	**1796**	620	631	601	630	634	595	632	601	**4945**	**8021**
2	6247	6245	**12491**	1399	1444	1712	1503	1532	1407	1385	1525	1528	1385	1386	1474	**17677**	2965	2967	2950	2961	2957	2950	2967	2963	**23680**	**53848**
3	7922	7921	**15843**	7891	7681	6808	6676	7053	6801	6627	6976	6983	6857	6871	6571	**83793**	16136	16155	16100	16094	16139	16110	16109	16133	**128974**	**228610**
4	857	850	**1706**	168	167	168	143	200	178	154	160	162	168	170	-	**1838**	1549	1569	1535	1563	1539	1537	1535	1573	**12404**	**15949**
5	3553	3552	**7105**	2080	2079	2078	2079	2080	2080	2079	2079	2080	2079	2079	2080	**24955**	2879	2878	2879	2878	2879	2878	2879	2879	**23027**	**55087**
6	6405	6403	**12808**	1368	1348	1428	1342	1399	1430	1396	1364	1327	1328	1316	1310	**16361**	3732	3692	3728	3705	3695	3698	3718	3720	**29687**	**58856**
7	1298	1297	**2596**	635	624	606	634	595	638	646	642	616	658	625	629	**7551**	4452	4488	4463	4458	4459	4499	4487	4494	**35800**	**45946**
8	3132	3132	**6264**	1770	1757	1820	1796	1771	1757	1815	1766	1814	1787	1792	1751	**21394**	9892	9923	9890	9898	9894	9891	9924	9928	**79241**	**106899**
9	3961	3960	**7921**	750	775	747	748	769	777	774	748	742	758	768	776	**9133**	3081	3101	3099	3086	3081	3079	3105	3112	**24747**	**41801**
10	4784	4783	**9566**	3077	3083	3091	3061	3099	3053	3035	3064	3085	3066	3085	3065	**36862**	7352	7346	7312	7320	7321	7361	7325	7359	**58694**	**105122**
11	5344	5344	**10688**	3723	3728	3715	3739	3736	3758	3685	3705	3707	3738	3746	3696	**44672**	3157	3096	3134	3095	3086	3091	3125	3112	**24893**	**80253**

Table IV: Results comparison between the total time (T_R) required in the 'as is' scenario S_R and the production time in the scenario simulated S_S in each workstation.

k / i	1			2			3			4			5			$\sum_{j,i} t_{p,i,j,k}$		ε_R
	S_R	S_S	Δ	S_R	S_S	Δ	S_R	S_S	Δ	S_R	S_S	Δ	S_R	S_S	Δ	S_R	S_S	
1	1291	1280	11	1690	1341	349	1529	1507	12	456	455	1	3575	3437	138	8541	8020	6.10 %
2	12616	12491	125	15796	13274	2522	17587	16284	1303	4566	4403	163	8246	7396	850	58811	53848	8.44 %
3	16159	15843	316	64397	62888	1509	126017	124523	1494	22452	20905	1547	5230	4451	779	234255	228610	2.41 %
4	1740	1706	34	1764	1389	375	9695	9010	685	483	449	34	3425	3394	31	17107	15948	6.78 %
5	7119	7105	14	18554	17179	1375	19520	18679	841	8296	7775	521	4767	4348	419	58256	55086	5.44 %
6	13032	12808	224	13401	12272	1129	22942	22231	711	4272	4088	184	8128	7457	671	61775	58856	4.73 %
7	2622	2596	26	5891	5664	227	32648	32293	355	1925	1887	38	3741	3506	235	46827	45946	1.88 %
8	6389	6264	125	17165	16042	1123	76916	75187	1729	5513	5353	160	4245	4054	191	110228	106900	3.02 %
9	8040	7921	119	8015	6851	1164	20136	19141	995	2292	2282	10	6016	5606	410	44499	41801	6.06 %
10	9748	9566	182	29062	27678	1384	52015	51551	464	9406	9184	222	7335	7142	193	107566	105121	2.27 %
11	10859	10688	171	33737	31094	2643	20223	20072	151	13848	13578	270	4902	4820	82	83569	80252	3.97 %
$\sum_{k} t_{p,i,j,k}$	**89615**	**88268**	**1347**	**209472**	**195672**	**13800**	**399508**	**390478**	**9030**	**73509**	**70359**	**3150**	**59610**	**55611**	**3999**	**831714**	**800388**	

Table V: Results comparison between the total time required in 'as is' scenario S_R and the total time required in the scenario simulated S_S, obtained adding the amount of time spent in queue ($\Delta = T - (\sum_i t_{p,i,k} + \sum_i t_{q,i,k})$); ε_T represents the total percentage of time saving.

	S_R	S_S		Δ [minutes]	Δ [hours] (rounded)	ε_T
k	T	$\sum_i t_{p,i,k}$	$\sum_i t_{q,i,k}$			
1	8541	8021	55	465	8	6.09 %
2	58811	53848	108	4855	81	8.26 %
3	234255	228610	93	5552	93	2.37 %
4	17107	15949	54	1104	18	6.45 %
5	58256	55087	103	3066	51	5.26 %
6	61775	58856	128	2791	47	4.52 %
7	46827	45946	93	788	13	1.68 %
8	110228	106899	97	3232	54	2.93 %
9	44499	41801	95	2603	43	5.85 %
10	107566	105121	159	2286	38	2.13 %
11	83569	80253	137	3179	53	3.80 %
∑	**831434**	**800391**	**1122**	**29921**	**499**	

This paper explores one of the several aspects assessed by the Digital Factory implementation approach. In this paper a proposal of a layout reconfiguration and a technological solution for the parts feeding system of the industrial plant has been analysed in order to reduce the production lead times using simulation. Furthermore simulation assists engineers and managers to find and analyse opportunities for improvements related to capacity, work-in-process flow, labour allocation, new product development and many other manufacturing issues.

The simulation results reveal that the new production system performances are definitely better than the real ones. In particular, the introduction of the conveyor system allows eliminating the waiting time spent for the batch being completed and the time spent by the operators for materials handling between the work centres. Total time reduction depends from individual orders, these values ranges from 1.6 to 8.6 %.

This time reduction results in a substantial total cost reduction for the company. The reduced working hours will be around 500 and considering the average hourly cost of an employee is 14.2 € the company will save approximately 7.100 €. Moreover the reduced lead time allows company to acquire new orders and new customers.

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