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Analysis of the relationship between available information and performance in facility logistics

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Abstract Regarding the amount of processed information, there are two basic approaches to handle today's increasing requirements for facility logistics systems. First, the collection of all achievable information about the system and its load in order to predict future system states accurately; theoretically, this could lead to optimal results. Second, the use of rather simple heuristics with less need for information but higher flexibility and robustness instead. This approach is for instance being realized with the Internet of Things in facility logistics. This paper analyses the dependency of throughput time and capacity utilization on available information for two limiting cases. While a 'best possible' case assumes that the material flow control has all relevant information about the system and loads, a 'worst reasonable' case considers the same for very limited information. The influence of layout, throughput, and element availabilities on this relationship is analyzed for both cases on the basis of a scalable generic test system and steady flow situations. In total, nine simulation studies are conducted and analyzed regarding throughput time and element utilization as performance indicators. Implications for the importance of information on performance depending on system complexity are discussed, and directions for further research are provided.

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1 Introduction

It is beyond doubt that for most companies, the need to operate effectively and efficiently increased significantly over the last years. At the same time, companies and their environment became more complex, be it due to global markets, shorter product life cycles, or a trend toward more individualized products [1, 2]. Obviously, this does not only affect supply chain management and manufacturing but also facility logistics. Thus, the dilemma between short throughput time, high schedule reliability, low WIP level, and high utilization rates [3] became even harder to resolve.

In order to evaluate the influence of the amount of information on system performance in general, it seems promising to evaluate (hypothetical) best possible and worst reasonable cases. This not only allows to determine a corridor between upper and lower system performance for given layouts and element characteristics but also provides an opportunity to review any given real control strategy. It is the aim of this paper to introduce this idea by analyzing a test system based on a scalable generic layout.

The remainder of the paper is organized as follows. Section 2 gives a brief overview of the current literature on the relationship between available information and system performance and introduces the concept of a 'best possible' and 'worst reasonable' case regarding available information. Section 3 defines a test system for which the relationship between available information and system performance is analyzed. In Sect. 4, the results of the conducted simulations are presented and discussed.

2 The relationship between available information and system performance

In general, the performance of a given facility logistics system is expected to increase with increasing available—and processed—information. Bullinger and ten Hompel [4] note the synchronization between material and information flow as one of the four basic axioms of facility logistics. Mikosch [5] mentions that most centrally organized control systems cannot work efficiently due to the fact that material and information flows are not synchronized sufficiently. The relationship between the amount of available information and performance is also of interest in adjacent fields of facility logistics. Van der Vorst et al. [6] show in a case study for a complete supply chain that real-time information systems are required for efficient and effective supply chains. For manufacturing, Wiendahl and Breithaupt [7] develop a closed-loop control for a PPC based on the relevant logistical objectives to synchronize capacity and work. Numerous other examples can be found in literature and praxis.

As a result, it could be argued that the best performance can be achieved by collecting all possible information about a material flow system and its load, simulating the results of possible control options and thus finding an optimal solution for any given situation. However, the collection and processing of information is not only expensive but possibly also causes significant dead times which is especially relevant in conjunction with real-time requirements [8]. Therefore, a different approach based on decentralized control systems with rather simple heuristics and less need for information is currently being subject to intensive research in facility logistics. Many authors provide a vision for the Internet of Things based on independent agents [5, 9–11]. Follert et al. [12] and ten Hompel et al. [13] show in a simulation study that an agent-based approach allows controlling the complete baggage handling system of a major airport with less than 400 lines of code. Scholz-Reiter et al. [14] and Armbruster et al. [15] analyze insect-inspired approaches based on the reduction of complex problems into simple heuristics. These approaches can lead to optimal results if applied by many insects—respectively, software agents for technical systems [14]. For a test scenario, Scholz-Reiter et al. show that positive properties of the biological example like flexibility are transferable to material flow systems.

The aim of this paper is to provide further insight into the relationship between information and performance in facility logistics in a broader sense.

Figure 1 shows a simplified model of a facility logistics material flow system based on a feedback loop between material flow installation and material flow control. Thereby, the quality of decisions depends on two determinants:

- Which information is available?
- How are decisions made based on the available information?

For an analysis of the dependency of system performance on available information, it was assumed that all information is always being used in the best possible way. Particularly, this implies that the amount of available information is the only determinant for system performance in a given system and load situation.

For the remainder of this paper, two limiting cases are distinguished. A ‘best possible’ case assumes that the material flow control has all relevant information about the system (e.g., layout, elements, past, current, and future loads), thus leading to the best possible decisions. This is not feasible for real systems but could be approximated by measuring the system states and predicting loads as accurate as possible.

In contrast, the ‘worst reasonable’ case assumes that material flow control has very limited access to information. The amount of information in this case is limited to the absolute minimum necessary to avoid completely arbitrary decisions. Table 1 gives an overview of available information for both cases.

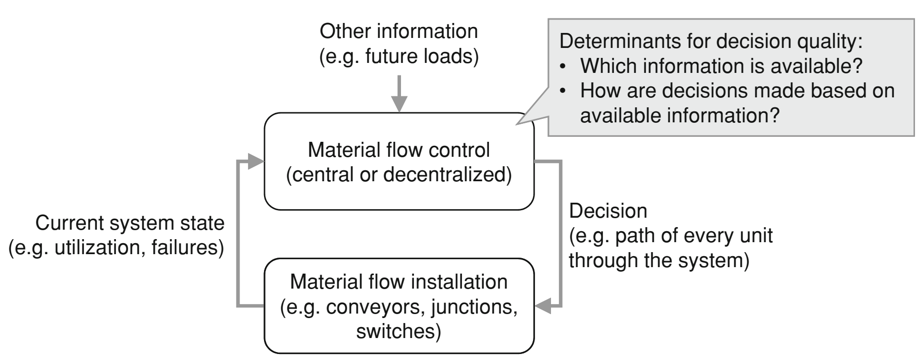

Fig. 1 Simplified model of a material flow system

Table 1 Available information for the 'best possible' and 'worst reasonable' case

Dimension	'Best possible' case	'Worst reasonable' case
System layout	Possible routes for all source–sink relationships	Possible routes for all source–sink relationships
	Basic throughput time for all routes	Basic throughput time for all routes
	Influence of connection between routes on throughput times (additional throughput time)	None
System elements	Dependency of throughput time and utilization on throughput for all elements	None
Availability of system elements	All failures of all elements for all periods	Momentary failures of routes
Loads	All past and future loads for all source–sink relationships for any given period	None

3 Introduction of a test system

In order to evaluate the differences between both cases quantitatively, it is necessary to define a suited test system. We decided to evaluate continuous conveyor systems due to their importance in facility logistics. As a first step, the system is composed of junctions, switches, and conveyors only. No storage elements are considered; thus, the analysis of system performance does not include WIP levels and schedule reliability.

For the test system, all material flows are assumed to be steady or quasi-steady, i.e., decomposable into steady flow periods of sufficient length. This is a fair approximation for steady flows or long observation periods. The analysis of unsteady element characteristics is not in focus of this paper.

3.1 Layout

The layout—i.e., the combination of and the connection between the elements—should fulfill the following specifications

- Suited to test differences: In order to test differences between both cases, it is favorable to use a highly connected system as system performance strongly depends on load handling at junction elements. This can be ensured by constructing a system with two or more routes for each source–sink relationship.
- Well-defined scalability: Generally, the performance difference between the best possible and worst reasonable case is dependent on the size and complexity of the system. Therefore, it was necessary to find a layout which is scalable in a well-defined way—ideally by one variable which affects both size and complexity.
- Easy to analyze: The dependency of performance on system size/complexity should be easy and efficient to analyze.

Typical Manhattan shaped test layouts fulfill the first and last criterion very well but show an unfavorable behavior regarding scalability. Usually, the number of possible routes between sources and sinks is not equal for all source–sink relationships and also changes irregularly with growing system size. Figure 2 shows a modified Manhattan shaped layout which fulfills all requirements. It has one source and one sink with multiple routes between them. While it is scalable over the number n of junctions in the system (Fig. 3), it is still comparatively easy to analyze and shows some favorable properties. It is easy to see that the number of elements is determined only by the number of junctions n. If n increases by one, the number of switches increases by one as well while the number of conveyors increases by 3.

Furthermore, the number of routes r between the source and the sink is only dependent on n, thus fulfilling the Fibonacci sequence $r_n = r_{n-1} + r_{n-2}$. This can be shown by complete induction:

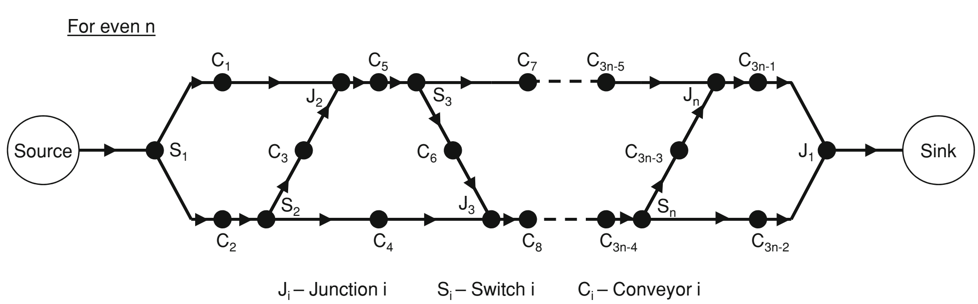

Fig. 2 Proposed layout for even number n of switches/junctions

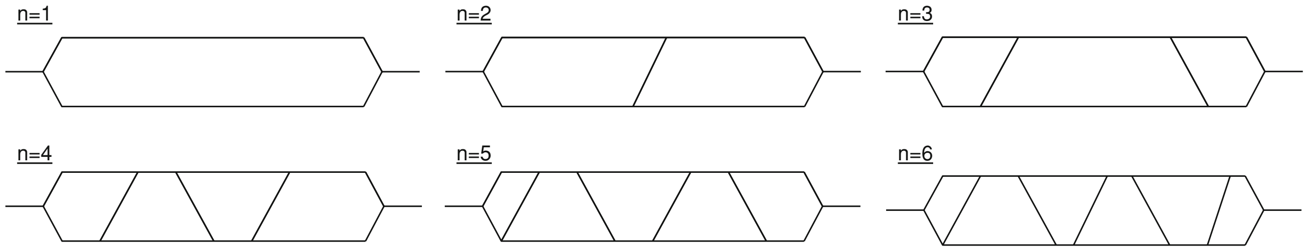

Fig. 3 Scalability of the proposed layout with the number of junctions n

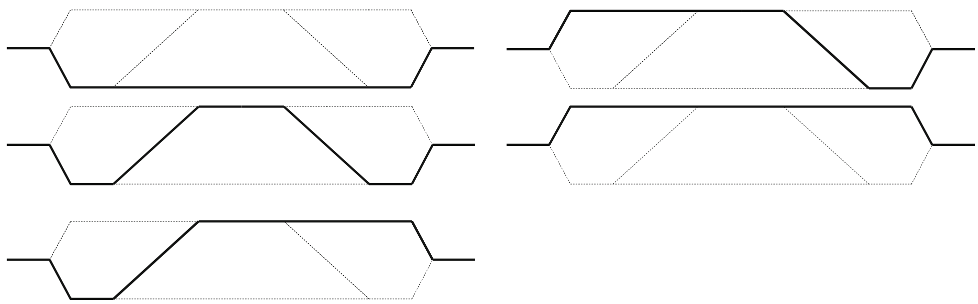

Fig. 4 Possible routes for $n = 3$

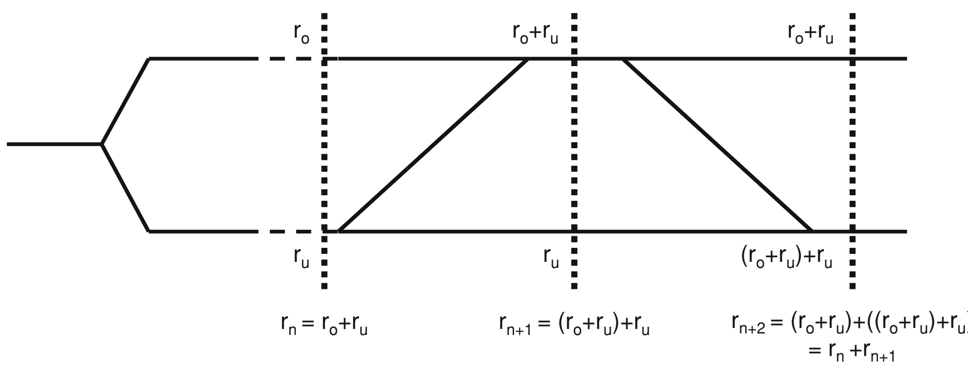

Fig. 5 Induction step $n \rightarrow n + 2$

- The number of routes for $n = 1,2$ is [2, 3]
- The number of routes for $n = 3$ is 5 (Fig. 4)
- In general, it holds for this layout that $r_{n+2} = r_{n+1} + r_n$ (Fig. 5)

Table 2 shows important basic properties of the proposed layout. It can be shown that they lead to many more regularities for this layout, e.g.,

- the elements on every route for every size can be determined by a simple algorithm,
- the conveyors upstream of every junction are easy to identify which is important to calculate additional throughput times, and
- the number of routes through each element follows the Fibonacci series.

Table 2 Some properties of the proposed layout

i	Total routes	# Elements	# Junctions	# Switches	# Conveyors
1	2	4	1	1	2
2	3	9	2	2	5
3	5	14	3	3	8
4	8	19	4	4	11
5	13	24	5	5	14
6	21	29	6	6	17
...	...	...	...	...	...
n	$r_{n-1} + r_{n-2} = \frac{1}{\sqrt{5}}\left[\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n\right]$	$5n-1$	n	n	$3n-1$

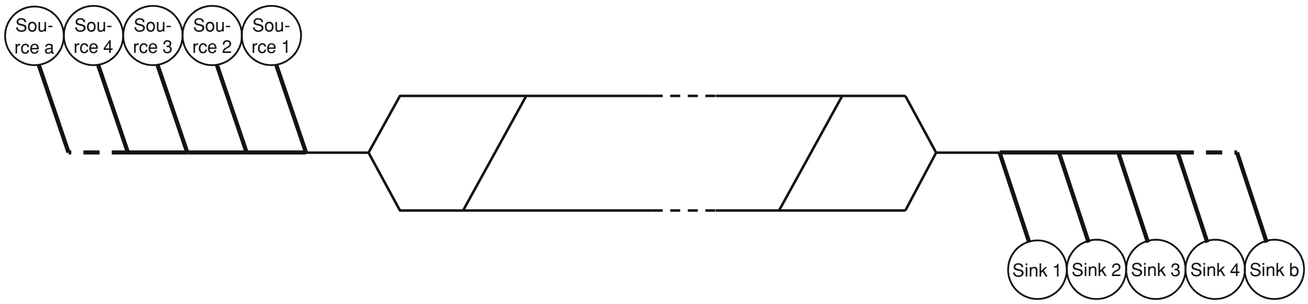

Fig. 6 Expansion of proposed layout with *a* sources and *b* sinks

Please note that it is possible to expand the number of sources and sinks as shown in Fig. 6. This allows constructing a highly connected test layout with the same number of routes between every source and sink. In that case, the number of elements shown in Table 2 has to be increased by $a-1$ junctions, $b-1$ switches, and $2a+2b-2$ conveyors.

As this paper focuses on steady material flows, it is possible to combine all possible sources and sinks at switch S_1 respective junction J_1. Therefore, the expansion with multiple sources and sinks is not analyzed further in this paper.

3.2 Element characteristics

In order to define the worst reasonable and best possible case for the test system, it is necessary to define the characteristics of the used elements, i.e., the dependency of throughput time and maximum capacity utilization on throughput.

Switches and conveyors are modeled as simple time delay elements with a maximum capacity and a specific availability. The throughput time of these elements is assumed to be constant in time and independent on throughput. In the remainder of this paper, the part of the throughput time independent from throughput will be called 'basic throughput time'.

Junction elements are modeled as a composition of constant throughput time accounting for conveyor elements in the junction and variable throughput time dependent on throughput accounting for buffer elements in the junction: $\mathrm{TPT}_{\mathrm{Junction}} = \mathrm{const.} + f(\dot{N}_1, \dot{N}_2)$. Here, the constant component is part of the basic throughput time as well, while the variable part will be referred to as 'additional throughput time' in the following. Figure 7 shows a schematic diagram of a junction element with (constant) inflows $\dot{N}_1$ and $\dot{N}_2$, an outflow $\dot{N}_3$, two buffers with filling levels $b_1(t)$ and $b_2(t)$, and constant time delay elements t_{C1}, t_{C2} and t_{C3} to represent conveyors within the junction. The outflow $\dot{N}_3$ shall be limited by $\dot{N}_{\max}$.

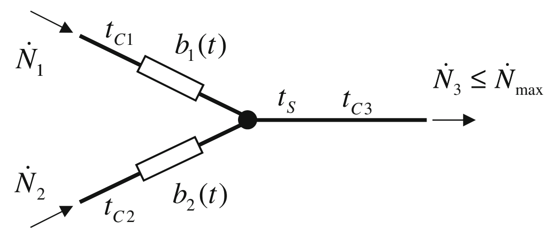

Fig. 7 The junction element

The additional throughput time for junction elements depends not only on the inflow and outflow but also heavily on the chosen switching strategy [16, 17]. For this work, both input flows for each junction are considered to be equally important, and no obvious main direction can be defined. Furthermore, the junctions are modeled to work in batch processing mode as opposed to a stochastic switching strategy (FIFO).

Großeschallau [16] defines possible switching strategies for junctions with equally important inflows in batch processing mode (i.e., constant cycle time, variable cycle time, and waiting queue monitoring). In this work, a variable cycle time with slightly adapted waiting queue monitoring has been analyzed. In contrast to constant cycle times, it is possible to define global parameters (i.e., independent on the relation of $\dot{N}_1$ to $\dot{N}_2$ for the considered junction) for this strategy which lead to optimal behavior of the junction [16]. Unlike pure waiting queue monitoring strategies, however, the chosen strategy provides a defined maximum throughput time for both paths through the junction. Nevertheless, it shows good performance regarding average throughput time in dependency of throughput. For these reasons, results seem to be transferrable to real applications with optimized switching strategies for each junction.

For the used switching strategy, the relationship between switch position, input and output flows, and buffer filling levels is shown in Fig. 8. The junction switches position if it is not possible to maintain the defined maximum outflow $\dot{N}_{\max}$ with the current switching position and if the buffer of

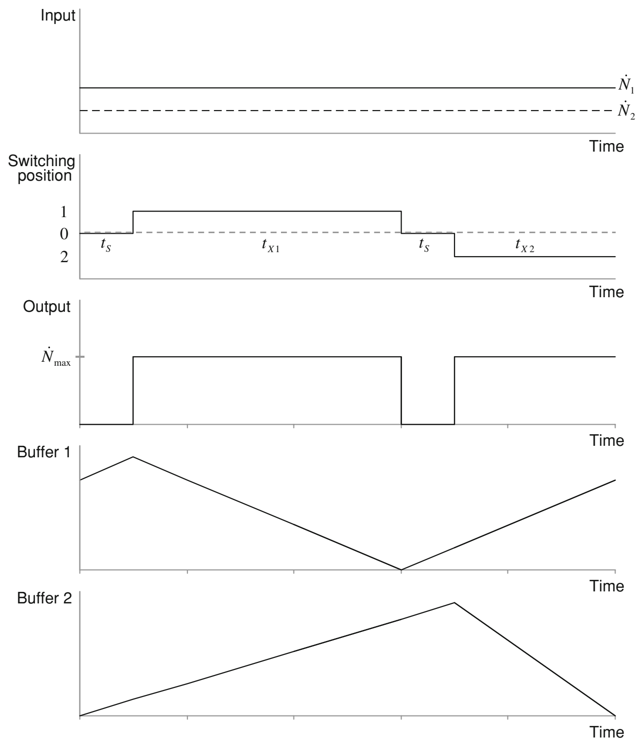

Fig. 8 Relationship between input, switching position, output, and buffer size for junction element

the other branch is not empty. Every switching operation lasts t_S seconds, the maximum dwell time per switching position is limited and shall be denoted by $t^*/2$. Continuity requires that

$$t_{X1}\left(\dot{N}_{max} - \dot{N}_1\right) = (2t_S + t_{X2})\dot{N}_1 \quad (1)$$

and

$$t_{X2}\left(\dot{N}_{max} - \dot{N}_2\right) = (2t_S + t_{X1})\dot{N}_2 \quad (2)$$

These equations can be transformed into

$$t_{X1} = 2t_S \frac{\dot{N}_1}{\dot{N}_{max} - \dot{N}_1 - \dot{N}_2} \quad (3)$$

and

$$t_{X2} = 2t_S \frac{\dot{N}_2}{\dot{N}_{max} - \dot{N}_1 - \dot{N}_2} \quad (4)$$

Thus, the average variable part of throughput time for both paths is

$$\overline{\mathrm{TPT}_1} = \frac{\int b_1(t)dt}{\int dt} = t_S \frac{\dot{N}_{max} - \dot{N}_1}{\dot{N}_{max} - \dot{N}_1 - \dot{N}_2} \quad (5)$$

and

$$\overline{\mathrm{TPT}_2} = \frac{\int b_2(t)dt}{\int dt} = t_S \frac{\dot{N}_{max} - \dot{N}_2}{\dot{N}_{max} - \dot{N}_1 - \dot{N}_2} \quad (6)$$

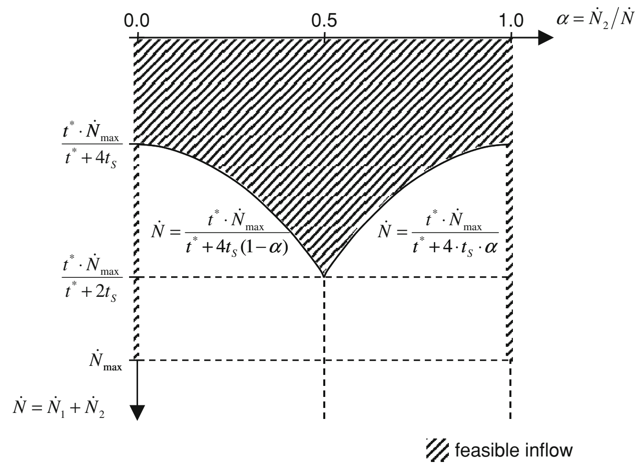

Fig. 9 Maximum throughput of junction depending on distribution of inflows, switching time, maximum outflow, and maximum dwell time per position

With $\dot{N} = \dot{N}_1 + \dot{N}_2$ and $\alpha = \dot{N}_2/\dot{N}$ the average variable part of throughput time through the buffers can be expressed as

$$\overline{\mathrm{TPT}} = (1-\alpha)\overline{\mathrm{TPT}_1} + \alpha\overline{\mathrm{TPT}_2} = t_S\left(1 + \frac{2\alpha\dot{N}(1-\alpha)}{\dot{N}_{max} - \dot{N}}\right) \quad (7)$$

Note that Eq. 7 only holds for $0<\alpha<1$. Otherwise, the variable part of throughput time equals zero as there are no switching operations if one buffer is not filled; therefore, $\alpha = 0$ or $\alpha = 1$ leads to an additional throughput time of zero for the junction element.

If $\dot{N}_1 > \dot{N}_2$, the dwell time in position 1 is greater than the dwell time in position 2. Thus, it is necessary that $t_{X1} \le \frac{t^*}{2}$. Applied to Eq. 3, this gives

$$\dot{N} \le \frac{t^*\dot{N}_{max}}{t^* + 4t_S(1-\alpha)} \quad (8)$$

The case $\dot{N}_1 < \dot{N}_2$ can be treated analogously. Figure 9 shows the resulting limits for feasible total inflow $\dot{N}$ depending on the distribution of inflow α.

3.3 Control strategy based on available information

Given the definitions in Sects. 3.1 and 3.2, it is possible to define the best possible and worst reasonable case for the test system. It is assumed that all routes through the system have the same basic throughput time for every length. This can be assured by solving the equation

$$R \cdot \overrightarrow{\mathrm{TPT}} = c \cdot \vec{1} \quad (9)$$

for each system size where R is a $[r \times (5n-1)]$ matrix containing the elements on every route, $\overrightarrow{\mathrm{TPT}}$ is a vector containing the basic throughput times of all elements, c is

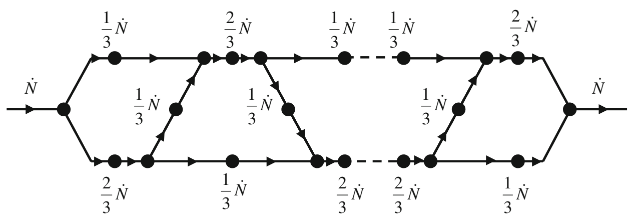

Fig. 10 Element utilization for the best possible case

an arbitrary constant, $\overrightarrow{1}$ is the unity vector, and r is the number of routes through the system for the given size.

As introduced in Sect. 2, the worst reasonable case only provides information about the basic throughput time for all available routes. Therefore, it is reasonable to distribute the total load equally to all available routes at any time. Obviously, if no route is available in case of a total system failure, there will be no flow through the system.

The best possible case provides all information about the system, especially on element characteristics, the layout, and all past and future element failures. First, assume that no element failures occur. In order to optimize throughput time, only one route through the system should be used at any point of time. Otherwise, there would be at least one junction element with $0 < \alpha < 1$, thus extending throughput times above the basic throughput time (Sect. 3.2). Yet if only one route is used for the whole period under consideration, the average utilization of the elements would be fairly unequal. Therefore, it makes sense to use only one route at one point of time but change the used routes over time in order to provide a balanced average utilization of all elements.

It can be shown that Fig. 10 represents the best possible average element utilization in the period under consideration if there are no element failures. Table 3 shows the resulting utilization of elements.

To achieve these element utilizations, it is necessary to use all system routes for time shares $\overrightarrow{x}$ of the total period under consideration. Here, $\overrightarrow{x}$ is a $[r \times 1]$ vector which can be calculated by solving $R^{T}\overrightarrow{x} = \overrightarrow{b}$ where $\overrightarrow{b}$ is the desired utilization rate of every element (Fig. 10).

If element failures occur, it is possible to maintain the same average element utilization rates if the time share of no failure periods is high enough and if there is no total system failure (i.e., there is at least one route through the system left). As for the best possible case information about all past and future failures is available, periods of no failure as well as most periods with sparse failed elements can be used to balance the missing load of elements which are caused by total failure periods. It can be shown that this balancing needs at most a time share of no failure twice as long as the time shares with failure. Obviously, total system failures cannot be balanced in the same way as this would require overloading the system in times of no failure. In the following, it is assumed that the best possible strategy can balance element utilization to the values listed in Table 3 except for periods with total system failure.

Table 3 Utilization for best possible case

ø Utilization	# of elements
$^1/_3\dot{N}$	$2n-1$
$^2/_3\dot{N}$	$3n-2$
$\dot{N}$	2

4 Simulation study

To evaluate the test system, nine simulations have been conducted, all of them considering steady flows. The layout is designed as described in Sect. 3.1 for $n = 1-20$ junctions. All switches and conveyors are considered to have a higher capacity as the maximum inflow $\dot{N}$, which equals 1.0 units per second. Junction elements are modeled as described in Sect. 3.2 having a switching time $t_S = 3$s and a maximum outflow $\dot{N}_{max}$ of 1.8 units per second. In order to prevent overfilling of buffers, t^* is chosen to be 15 s; thus, the requirement of Eq. 8 is met for any $\dot{N}$. The chosen basic throughput times are equal for all routes of a system size n and can be found in Table 4.

These values are realistic for systems in facility logistics. Typical speeds for continuous conveyor systems are in the range of 0.5 m per second [18]. For $n = 20$, this leads to (realistic) element lengths between 2.5 and 20.0 m with an average of 7.1 m. The calculated additional throughput times, however, might even be slightly above realistic values: Considering a conveying speed of 0.5 m per second and the used inflow $\dot{N}$, the length of transported units is minimally 0.5 m. The effective length would even be less which seems rather small for most real transport units [17]. On the other hand, the chosen switching time $t_S = 3$s is comparatively high. Considering Eq. 7, it can be seen that this leads to an overstatement of additional throughput times. Therefore, in reality, it would be expected that the relative difference in throughput time between best possible and worst case is by trend less than the calculated values.

Table 4 Basic throughput time depending on n

n	1	2	3	4	5	6	7	8	9	10
TPT	15	40	65	100	135	170	205	240	275	310
n	11	12	13	14	15	16	17	18	19	20
TPT	345	380	415	450	485	520	555	590	625	660

Table 5 Overview of conducted simulation studies

#	Availability of conveyors (%)	Availability of switches (%)	Availability of junctions (%)	Total inflow $\dot{N}$ (units/second)
1	100	100	100	1.000
2	99	99	99	1.000
3	99	99	99	0.125
4	99	99	99	0.250
5	99	99	99	0.375
6	99	99	99	0.500
7	99	99	99	0.625
8	99	99	99	0.750
9	99	99	99	0.875

Table 5 gives an overview of conducted simulations varying availability and inflow where availabilities are defined accordingly to VDI standards [19]. The failure of elements is simulated by averaging mutually independent random experiments which can be interpreted as time periods. For each of them, a random element failure pattern (for instance: switch 3 and conveyor 17 failed) is simulated by using element availabilities from Table 5. This procedure gives good results if the number of experiments is high enough. Figure 11 shows the convergence of minimum, average, and maximum element availability over the number of experiments. For 100,000 experiments, the averaged element availability for all experiments is maximal 0.9907, minimal 0.9892, and on average 0.9900. This gives a relative mistake less than 0.1%. All mentioned simulations have been conducted with 100,000 experiments and the data set shown in Fig. 11.

Figure 12a shows the resulting absolute values for throughput time depending on system size and complexity (depicted by the number of junctions n) and available information while Fig. 12b shows relative differences between best possible and worst reasonable case. As mentioned before, the difference between both cases might be overstated due to the chosen parameters of the simulation. Nevertheless, the corridor between both cases is fairly

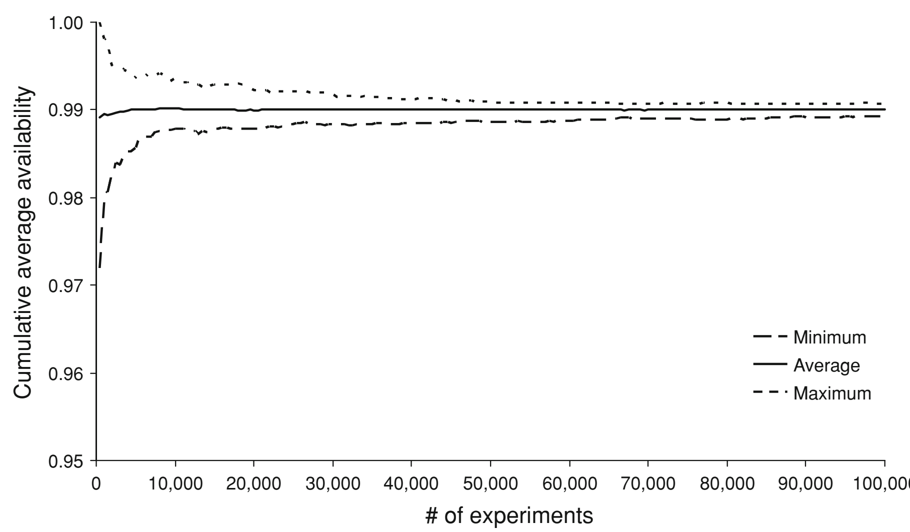

Fig. 11 Cumulative minimum, average, and maximum availability for all elements depending of number of experiments

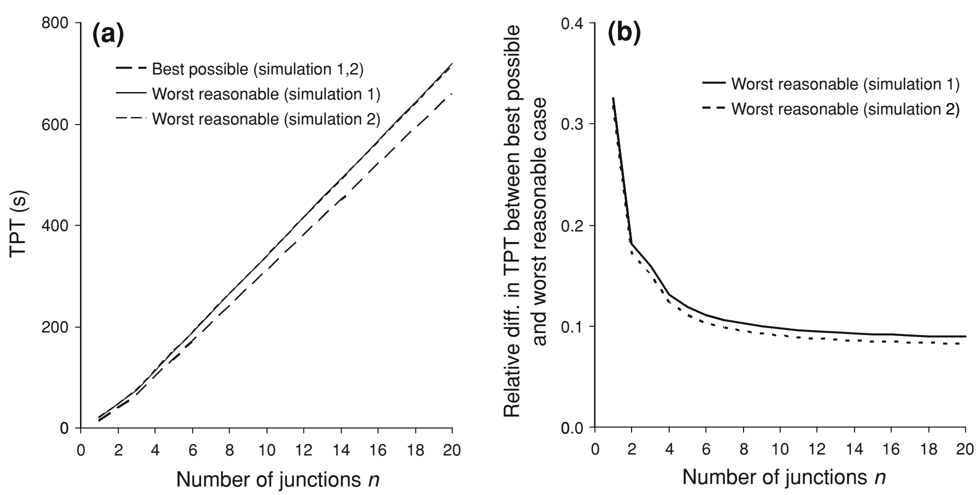

Fig. 12 Throughput time for simulation studies 1 and 2

small and becomes even smaller by considering the more realistic simulation 2 with element failures. For both, the relative difference between worst reasonable and best possible case is less than 10% for more complex systems ($n > 8$).

Figure 13 shows the dependency of additional throughput time on load and system size. Note, that for every n, the whole system seems to behave like a single junction. A curve-fit of a general form of Eq. 7

$$\overline{\mathrm{TPT}} = C_1 + \frac{C_2 \dot{N}}{C_3 - \dot{N}} \quad (10)$$

to the data shown in Fig. 13 using the method of least squares and a solver based on the Levenberg–Marquardt algorithm was conducted. For $n = 20$, the total residual

$$R = \sum (y_{\mathrm{m}} - y_{\mathrm{i}})^2 \quad (11)$$

is 1.35E-4 with y_{m} being the modeled values from Eq. 10.

Figure 14 shows a load histogram of simulation 1 for both cases. The effect of load balancing explained in Sect. 3.3 can be clearly seen: While the best possible case only shows loads of $1/3\dot{N}$, $2/3\dot{N}$, and $\dot{N}$, the profile of the worst reasonable case is more fragmented, which is a direct result of the equal load distribution to all routes. In the following, we will only consider 'inner elements', i.e., all elements besides switch 1 and junction 1. These two elements are constantly loaded with full system load and would distort results especially for small n. To quantify differences in element loads for both cases, it makes sense to analyze average element loads as well as the difference between maximum and minimum element load.

For simulations 2–9, it is necessary to adjust the results from total system failures. Otherwise, the combination of more elements for higher values of n would produce a higher probability of total system failure, which would lead to sinking average loads. The adjustment is done by dividing all element loads by one minus the proportion of experiments with total system failure. Average element loads for simulation 1 are shown in Fig. 15a and for simulation 2 in Fig. 15b. In both cases, values show clearly

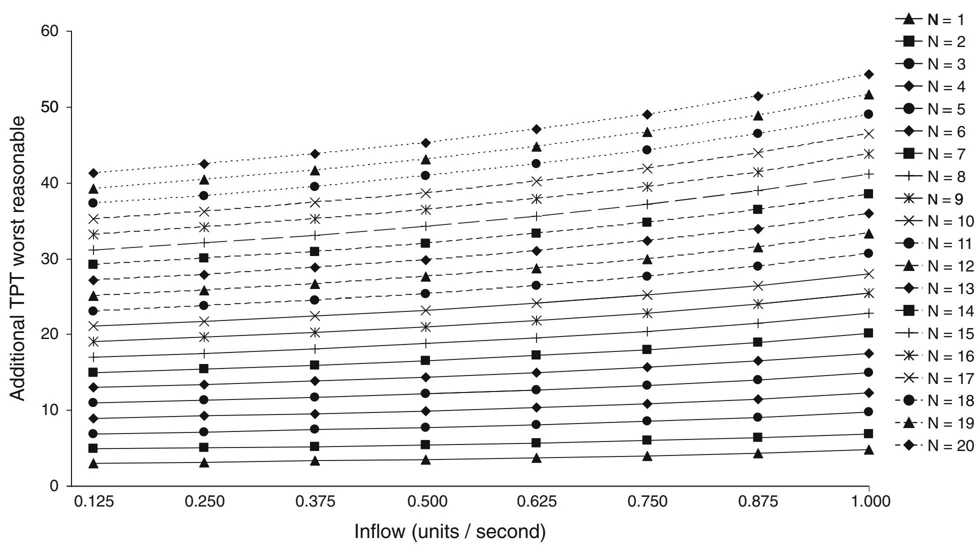

Fig. 13 Throughput time for simulation studies 2–9

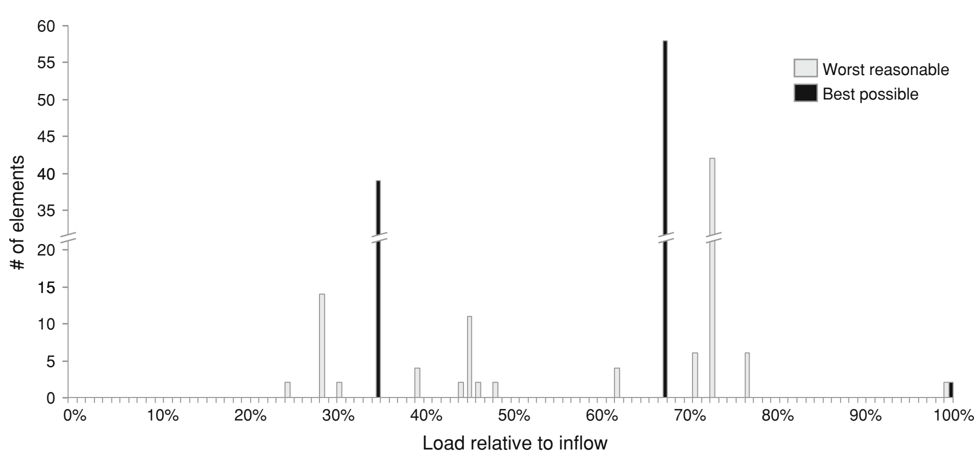

Fig. 14 Load histogram for simulation study 1 and $n = 20$

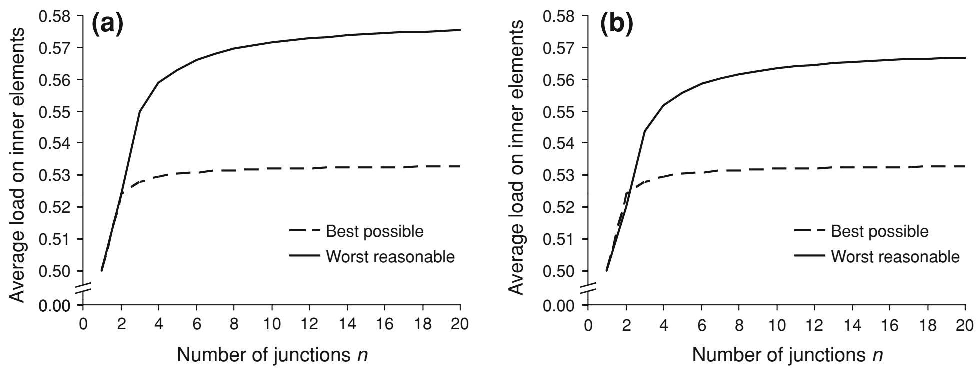

Fig. 15 Average load on elements for simulation 1 (**a**) and simulation 2 (**b**) (adjusted for total system failures)

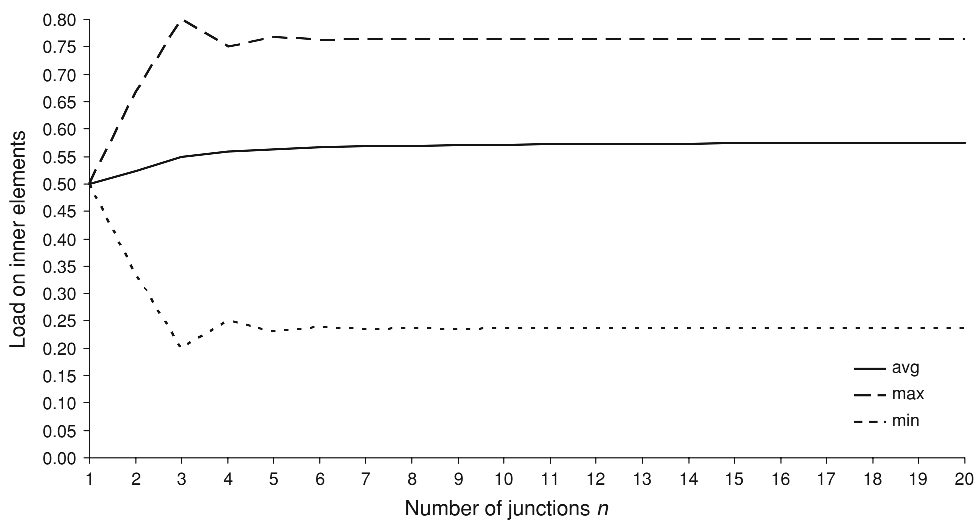

Fig. 16 Average, maximum, and minimum element load for simulation 1 (worst reasonable)

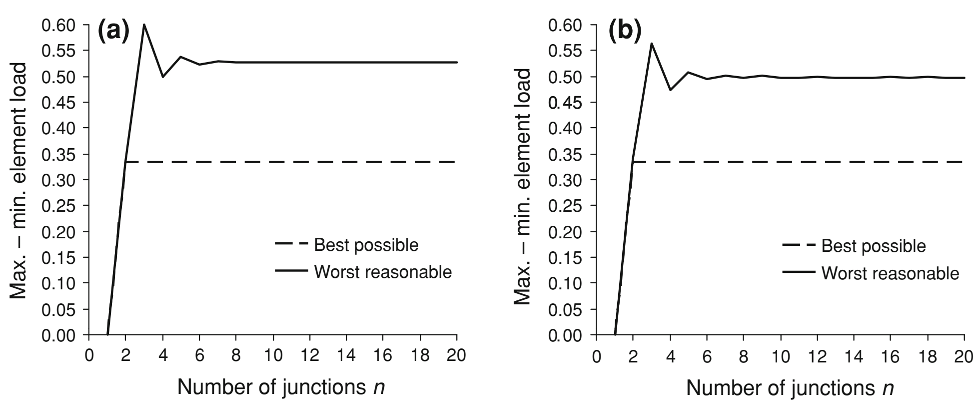

Fig. 17 Difference between maximum and minimum element load for simulation 1 (**a**) and simulation 2 (**b**)

converging behavior. For $n = 20$, the corridor between best possible and worst reasonable case is $\sim$8% (simulation 1) and $\sim$6% (simulation 2).

Figure 16 shows the spread of inner element loads for the worst reasonable case in simulation 1. The width of the spread is equal to the difference between maximum and minimum element load (Fig. 17). The relatively large difference between best possible and worst reasonable case can be explained by few elements with very high and low loads for the worst reasonable strategy (Fig. 14). Again, the difference becomes smaller, if the more realistic case with element failures is considered (Fig. 17b).

5 Conclusion and directions for further research

The analysis of best possible and worst reasonable cases provides a straightforward way to quantify the dependency between available information and performance of material flow systems. Generally, limiting cases are easier to describe than real strategies. This is especially true when the amount of available and processed information is considered. Nevertheless, they provide valuable insight as they not only give upper and lower bounds for system performance of real systems but also provide a scale to measure results of any real control strategy for a given system.

This paper analyzes a generic scalable layout with simplified characteristics of its three basic elements in steady load situations. Performance differences in throughput time and element utilization have been analyzed for different amounts of available information. Results for the test system suggest that differences between limiting cases are rather small. Often the difference between the best possible and the worst reasonable case is less than 10%. It is decreasing for high complexity of layout, low system load compared to maximum system load, and under consideration of element failures. This may be an indicator that for realistic systems, it could be better to choose a rather simple control strategy with less need for information but higher flexibility and robustness instead, as it is the case for decentralized material flow systems.

Possible directions for further research are the analysis of more complex cases, especially unsteady flows which cannot be handled with the given element characteristics. By considering dynamic system behavior and by the integration of buffer elements, other performance measures like schedule reliability and WIP levels could be analyzed as well.

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References

1. De Meyer A (1998) Manufacturing operations in Europe: where do we go next? Eur Manag J 16(3):262–271
2. Nyhuis P (2006) Logistic production operating curves—basic model of the Theory of Logistic Operating Curves. Ann CIRP 55(1):441–444
3. Schuh G, Wemhöner N, Friedrich C (2005) Scenario-based lifecycle analysis of manufacturing systems. In: Proceedings of the 38th CIRP international seminar on manufacturing systems, Florianopolis, Brazil, 2005
4. Bullinger HJ, ten Hompel M (eds) (2007) Internet der Dinge. Springer, Berlin
5. Mikosch F (2008) Zukunftsthemen der Logistik. Ind Manag 24(2):9–10
6. Van der Vorst JGA, Beulens AJM, de Wit W, van Beek P (1998) Supply chain management in food chains: improving performance by reducing uncertainty. Int Trans Oper Res 5(6):487–499
7. Wiendahl HP, Breithaupt JW (2000) Automatic production control applying control theory. Int J Prod Econ 63:33–46
8. ten Hompel M (2008) Intralogistik—Auf dem Weg vom Prozess zum Service. In: Baumgarten H (ed) Das Beste der Logistik. Innovationen, Strategien, Umsetzungen. Springer, Berlin, pp 103–110
9. Günthner W, Chisu R, Kuzmany F (2008) Das “Internet der Dinge”—Teil I. Intelligent verteilt. F+H, 7–8:422–425
10. Günthner W, Chisu R, Kuzmany F (2008) Das “Internet der Dinge”—Teil II. Steuern ohne Hierarchie. F+H, 9:494–497
11. Nagel L, Roidl M, Follert G (2008) The internet of things: on standardisation in the domain of intralogistics. Workshop ‘Producing Standards for the Internet of Things’, Conference Internet of Things 2008, Zurich, Switzerland
12. Follert G, Roidl M (2008) Evaluation of routing strategies for decentralized self-organization in large scale conveyor systems. Progress in Material Handling Research, Material Handling Institute, 160–184
13. ten Hompel M, Follert G, Roidl M (2008) Künstliche Intelligenz im Internet der Dinge: Die Zukunft der Materialflusssteuerung mit autonomen Agenten. Jahrbuch Logistik 2008:24–29
14. Scholz-Reiter B, Jagalski T, Bendul J (2007) Bienenalgorithmen zur Selbststeuerung logistischer Prozesse. Ind Manag 23(5):7–10
15. Armbruster D, de Beer C, Freitag M, Jagalski T, Ringhofer C (2006) Autonomous control of production networks using a pheromone approach. Physica A 363:104–114
16. Großeschallau W (1984) Materialflußrechnung. Springer, Berlin
17. Arnold D, Furmans K (2007) Materialfluss in Logistiksystemen. 5., erweiterte Auflage. Springer, Berlin
18. ten Hompel M, Jünemann R, Nagel L (2007) Materialflusssysteme. Förder- und Lagertechnik. 3., völlig neu bearbeitete Auflage. Springer, Berlin
19. Verein Deutscher Ingenieure (VDI) (2002) Technical availability of machines and production lines. Terms, definitions, determination of time periods and calculation. VDI-Richtlinien 3423(4):7–9