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Simulation-based evaluation of (de-)centralized supply chain management approaches

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1. Motivation for investigation

In last decades the "productivity paradox" has been debated – i.e. the empirical observation that high investment in information technology (IT) did not contribute significantly to productivity. Although several studies proved that *in general* IT has a significant and positive impact on firms output, the variation among different companies is enormous: Given the same large investments in IT, some firms are highly productive while others perform poorly (Brynjolfsson 1998, p. 52). One explanation is that benefits from IT investments have to be leveraged by adequate organizational changes and these adaptations are "time consuming, risky and costly" (Brynjolfsson 1998, p. 52).

Transactional systems such as Enterprise Resource Planning (ERP) systems have been implemented widely while analytical software like Supply Chain Management (SCM) Add-ons are adopted less by manufacturing companies (Patterson 2004, p. 21). In fact, the SCM software market is struggling the last years: The yearly prognosticated growth rates of about 50 % for the supply chain management (SCM) software industry at the beginning of the new century have not been reached. Revenues had fallen more than 10 % in 2001 and for the future only moderate annual growth between 7 and 15 % has been expected until 2010 (Roesgen 2007). SCM software promises high benefits in terms of savings and improvements in customer service level but at the same time accounts for high total cost of ownership. Frost&Sullivan prognosticated that especially sales of Supply Chain Planning (SCP) modules will underperform within the broad market of SCM software (Frost&Sullivan 2007). This type of decision support systems, also called Advanced Planning Systems (APS), belongs to the most expensive solutions due to the sophisticated optimization algorithms and the implementation complexity. However, "it is reasonable to believe that the appropriateness of using APS increases when the planning complexity increases" (Jonsson 2007, p. 821).

Given the uncertain cost-benefit profile of SCP software implementations two mayor research questions arise:

Which are alternative solutions for the implementation of APS and the required organization?

Which are the factors that account for a favorable cost-benefit profile?

This paper approaches the first question. The literature review focuses on research that deals with alternative solutions to the fully centralized organization. In the next section coordination theory is revisited as far as required for the understanding of the model to develop. Afterwards, information technology concepts are described that enable the different organizational concepts. The general findings are applied and detailed for the case of industrial networks. In the last chapter cost and benefit is quantified for alternative solutions by means of discrete event simulation.

2. Literature review

In the most recent research on SCM two fields of investigation are distinguished: "(1) supply chain planning with mathematical optimization models and (2) decentralized decision making" (Jung 2008, p. 350). The first research field mostly assumes that all functions are fully integrated in one central coordination department. Indeed, this is the underlying concept required for the implementation of SCP systems. The second research area is mainly driven by the fact that this "ideal" level of integration is not achievable because in inter-company networks several decision making units (DMU) with "independent decision criteria" and "private information" exist (Schneeweiss and Zimmer 2004, p. 688). this type of investigation deals with the performance gap between decentralized and fully integrated centralized organizations. The current paper also compares efficiency differences – but for intra-company networks. The fully centralized organization supported by APS is compared to several de-centralized organizational solutions. Therefore the area of decentralized decision making is of particular interest and main findings from recent research are summarized from heron. Schneeweiss and Zimmer investigate the performance of distributed decision making in a supplier-producer relationship. Results that the (reactive) anticipation of a few critical parameters – namely supplier's capacity situation and expansion cost – lead to a near-optimal performance. According to a recent study, decentralized supply chain planning performs well compared to the "ideal" centralized planning according to a recent study (Jung 2008). Minimum information sharing is proposed instead of unique, centralized database, i.e. only quantity information is exchanged while private information such as unit cost and available capacity is excluded.

SCP software is based on mathematical programming while ERP systems mostly apply MRP-logic. The principal drawbacks of traditional MRP-based coordination stem from the decomposition of the problem into un-capacitated single-item sub-problems that are solved independently and sequentially without backtracking (Pochet and Wolsey 2006, p. 63). According to an empirical study carried out within the Swedish manufacturing industry, the level of adoption of and satisfaction with certain sub-modules varies in function of the planning environment (Jonsson 2003). Main reasons for poor performance of MRP are uncertainties in demand and lead times (Dolgui 2007). Negative effects might be softened if parameters (safety stock and lead times, freezing and planning horizon, etc.) are selected with cautious. From these findings can be derived that the level of sub-optimality of MRP application (compared to APS) depends on a broad range of influence factors.

The research carried out in the field of mathematical optimization models is useful for the model building of the discrete event simulation. Within the last years has been recognized that deterministic optimization models (like implemented in APS) do not model adequately real world complexity. Therefore numerous authors combine analytical and simulation modeling sometimes referred to as "hybrid models". In an illustrative case study from the automotive industry mixed-integer linear programming is applied to solve the lot sizing and scheduling problem. The interfaced simulation model considers stochastic variability of endogenous (e.g. machine failure) and exogenous (e.g. demand) parameters. Economic performance of two configurations is compared – global integral optimization against local optimization. Jung et al. provide an even more sophisticated model for the chemical process industry. They combine two hybrid models – one for mid term coordination and another one for short term scheduling level (Jung et al. 2008). The study carried out by Garavelli applies heuristic rules rather than optimization (Garavelli 2003) – performance can be increased significantly although results are still sub-optimal.

All the above mentioned papers have in common that organization and technology cost is not considered. Therefore in this investigation alternative organizational and technological applications are compared in terms of benefits and cost.

3. Organization theory

In SCM literature "coordination" is mostly associated to the management of activities of independent economic entities. This coordination-oriented research investigates mechanisms such as quantity discounts, inventory control or contracting that are capable to align objectives among the independent decision makers. Oppositely, logistic-oriented research (that focuses on operational aspects such as production planning) views the supply chain as a fully integrated firm and the material flow is controlled by a single decision maker (Schneeweiss and Zimmer 2004, p. 689). Consequently, research focuses either de-centralized concepts for inter-company networks or assumes central planning in intra-company networks. However, de-centralized organizational design for intra-company networks has not been dealt with and is addressed in this paper.

3.1. Coordination by IT systems

Coordination is defined as "the act of managing interdependencies among activities" (Malone and Crowston 1994, p. 87). Four types of dependencies are distinguished to describe the relationship among resource and activity: flow, fit, sharing and assign.

Flow dependencies arise whenever one activity produces a resource that is used by another activity. Fit dependencies occur when multiple activities collectively produce a single resource. Sharing dependencies appear whenever multiple activities all use the same resource. Assign dependencies are observable if redundant resources exist that are able to perform an activity.

Several coordination mechanisms are available: Mutual adjustment, programming, and planning. Coordination is one of the "processes" to manage interdependencies; group-decision making, communication and sharing of common objects – such as information – is also suggested.

3.2. IT solutions for single locations

For single production locations modern ERP systems are still based on the MRP logic, i.e. the overall planning problem is decomposed in sub-problems that are solved sequentially. The MRP model basically delivers a JIT solution and therefore considers that latest dates combined with lot-sizing rules assure the optimal result. Master Production Scheduling (MPS) defines delivery dates and quantities individually for each group of finished products. Next, Rough Cut Capacity Planning (RCCP) determines the utilization of capacity resources. If orders cannot be placed in the required time buckets on the preferred machines, coordination mechanisms become necessary. If alternative machines are defined, the ERP system might switch orders to free capacity according to fixed rules. However, the decision does not assure optimality because it depends on the particular situation (i) which order type to move and (ii) which of the alternatives guarantees the best result. Furthermore, during the execution of subsequent task infeasibilities might occur due to material or capacity constraints.

If alternatives do not exist, orders might be switched to different time buckets. Then the MRP algorithm proposes adjusted dates and quantities for delivery and production on the following material and process levels. Again, neither optimality nor feasibility is assured so that iterative procedures might become necessary. Consequently, even though sophisticated ERP systems suggest possible solutions (Pochet and Wolsey 2006, p. 61) to resolve conflicts, human coordination is required to large extend.

Regarding coordination mechanisms, ERP systems are characterized by:

- Full capability to coordinate flow and fit dependencies. The requirements for material supply and production in terms of quantity and date are determined by the MRP algorithm efficiently.
- Low capability to coordinate sharing and assign dependencies. In case of resource conflicts, basic functionality of ERP systems is to postpone orders (sharing) or load redundant capacities according to a fix priority list (assign).

APS in contrast solves the integral planning problem simultaneously aiming at cost minimization or profit maximization based on optimization techniques. Therefore, in particular if sharing and assign dependencies exist, APS improves coordination results compared to ERP systems because the optimal solution is chosen out of a pool of possible ones. Furthermore, given that the IT system overtakes large part of the human coordinator's activities, headcount can be reduced. However, high cost is incurred when the implementation of APS is opted for, e.g. software acquisition, maintenance fees, implementation consultancy or internal expenses for the continuous process of master data up-dating.

In what follows we develop different organization forms to manage the material flow of industrial networks. The cost-benefit profile is evaluated for each organization form considering benefits from performance improvement and associated cost for organization and information technology.

4. Alternative organization forms

The proposed organization forms for the management of industrial networks differ by scope, sequence and type of coordination mechanisms employed. Figure 1 depicts the different coordination procedures.

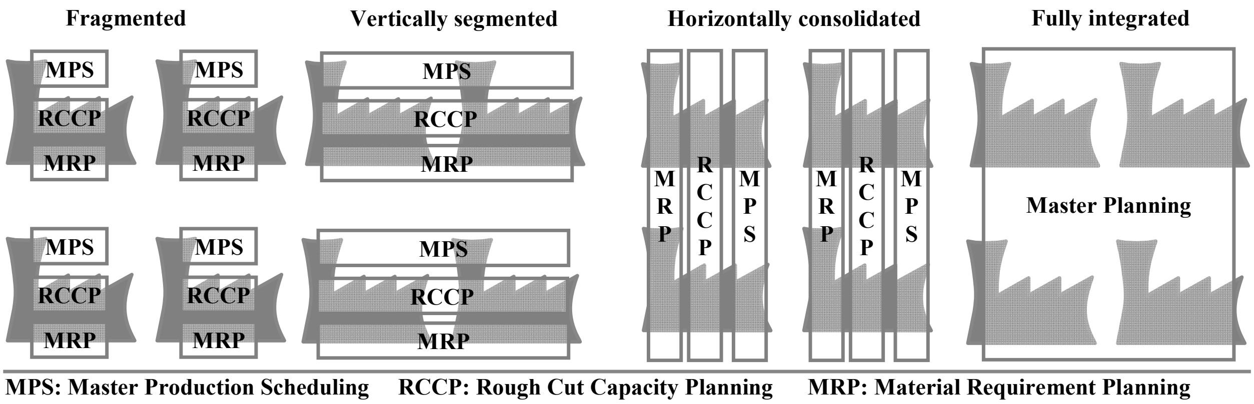


Figure 1. Detailed coordination procedures

In the most de-centralized form ("fragmented") the planning process is driven stage-wise upstream in the network. To demand markets (products, regions or clients) are associated in a static manner to 1-tier locations, those in turn to 2-tier site and so forth. With respect to the planning organization, each site disposes of local coordination unit for mid-term tactical decisions. Coordination is realized through communication and mutual adjustment. Once requirements are determined at downstream locations, forecasts are communicated upstream the supply chain in electronic format. From a technological point of view each site runs an autonomous ERP system, database integration is not necessary. This organization form is not adequate if sharing dependencies are complex because the employed mutual adjustment procedure between two sites is not efficient. If resource conflicts are numerous, the re-planning procedure among two facilities turns out to be costly and time-consuming. Due to the fix association of order types to locations, assign dependencies are not managed.

In case of “vertical segmented planning”, individual supply chains within the network are dedicated to markets based on the long-term strategy. Coordination is focused on dependencies within the segments. The local tactical planning tasks are merged and transferred to a corporate coordination unit. The MRP procedure is performed throughout the entire logistic segment and assures the coordination of sharing dependencies as far as the programmed heuristics (e.g. FIFO or fixed quotes) incorporated in common ERP system are capable to deliver feasible results. The nature of MRP leads to the typically sequential management of dependencies, beginning at 1-tier facilities with material coordination followed by capacity coordination and rolling back upstream the vertical segment. The organization structure does not take into account assign dependencies among segments. Compared to the basic organization form the main advantage is the immediate and automatic transformation of downstream demand in upstream requirement. Technological condition is a segment-wide ERP system with integrated database. The system is employed similar to a single location application. Due to the limited planning functionality of ERP systems, human planners still are widely required to realize plan changes. Nevertheless, large extend of the coordination is assumed by IT. Consequently, re-planning can be performed at notably lower organizational cost.

“Horizontally consolidated planning” prioritizes assign dependencies. Firstly, orders are allocated on finished product level to locations. The coordination of these assign dependencies is supported by the ERP system although only simple heuristic rules are available. Once the decision is made on finished product level, the MRP procedure is executed for the next tier-level. Sharing dependencies have to be coordinated after each allocation step. If infeasibilities occur during the planning process that cannot be solved, re-allocation on downstream levels becomes necessary. A network-wide ERP system is required to implement this organization form. However, given that ERP systems do support the management of assign dependencies only in a rudimentary manner, human planning capabilities are required to a large extend. In case that infeasibility occurs, intensive and time-consuming coordination procedures become necessary.

The most complex organization form (“fully integrated”) considers all dependencies simultaneously. The central planning unit neither allocates orders to fixed vertical segment nor to process levels but situation-dependent to internal supply chains. Consequently, production and supply programs of each location change dynamically. This planning procedure assures optimal results and minimum re-planning necessity but requires the implantation and maintenance of costly APS.

Table 1 summarizes the coordination mechanisms applied for the described organization forms and indicates the correspondent IT support.

Table 1. Organization forms, coordination mechanisms and IT solutions

Organization / Dependency	Fragmented	Vertically segmented	Horizontally consolidated	Fully integrated
Flow/Fit	Communication	Programming	Programming	Programming
Sharing	Mutual adjustment	Programming	Programming	Planning

Assign	n. a.	n. a.	Heuristic rules	Planning
IT solution	**Local ERP**	**Integrated ERP**	**Integrated ERP**	**APS**

5. Valuation model

The overall efficiency is driven by three cost categories. Improved coordination procedures result in better logistic performance thanks to reduced stocks, increased capacity utilization, shortened lead times, etc. In this investigation logistic performance is represented by transportation, production and holding cost. Customer service level is quantified by lost margins. The gap between the optimal results in the best performing organization and those from alternative, lower performing organization is called autonomy cost. To avoid autonomy cost more complex but costly coordination mechanisms and instruments can be applied. Thus, the overall efficiency is characterized by the manufacturing and logistics sub-optimality (autonomy cost), organizational design (organization cost) and IT systems (technology cost).

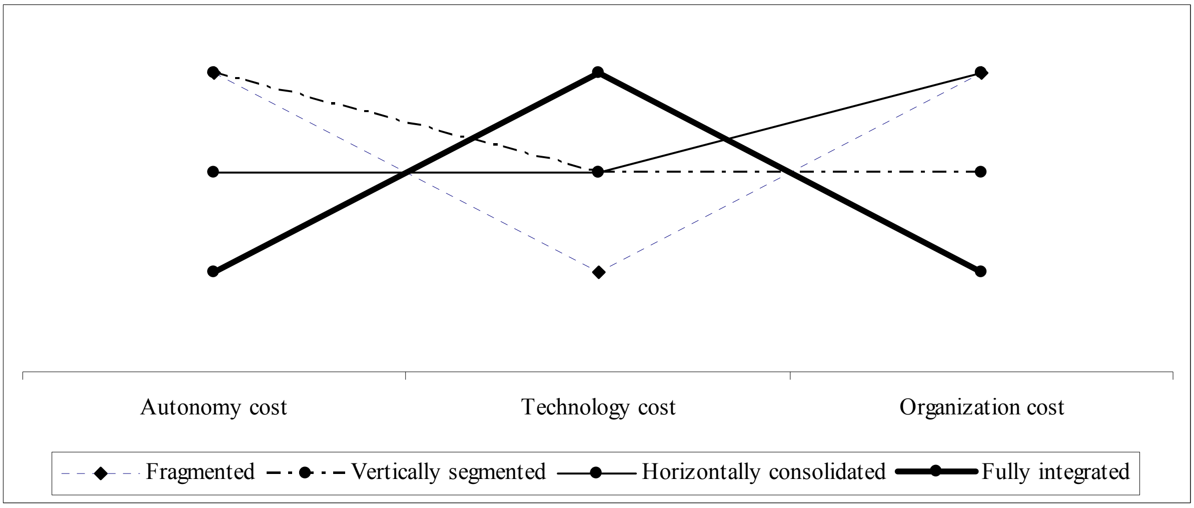


Figure 2. Organization forms for industrial network management

In Figure 2 the relative cost incurred with any of the four organization forms is represented. Autonomy cost is equally high in case of fragmented and vertically segmented coordination. The difference between both forms stems from other cost categories: the vertically segmented form requires investment for the enterprise-wide integration of local ERP systems (see technology cost), but shall achieve a reduction in organization cost. The integrated ERP system assumes the coordination of flow and sharing dependencies, i.e. the entire process of communicating and adjustment of supply requirement upstream the supply chain is absorbed out by IT. Compared to the vertically segmented form, the horizontally consolidated form introduces additional activities, i.e. consolidation of similar requirements and the assignment of orders to alternative locations. Consequently, on the one hand organization cost increases; on the other hand autonomy cost should be reduced. In the case of fully integrated organization, high technology cost is opposed to a reduction in autonomy cost and organization cost. Autonomy cost is minimized thanks to simultaneous optimization of the network master plan. Organization cost is minimized because planning activities are widely transferred from the human planner to the IT system.

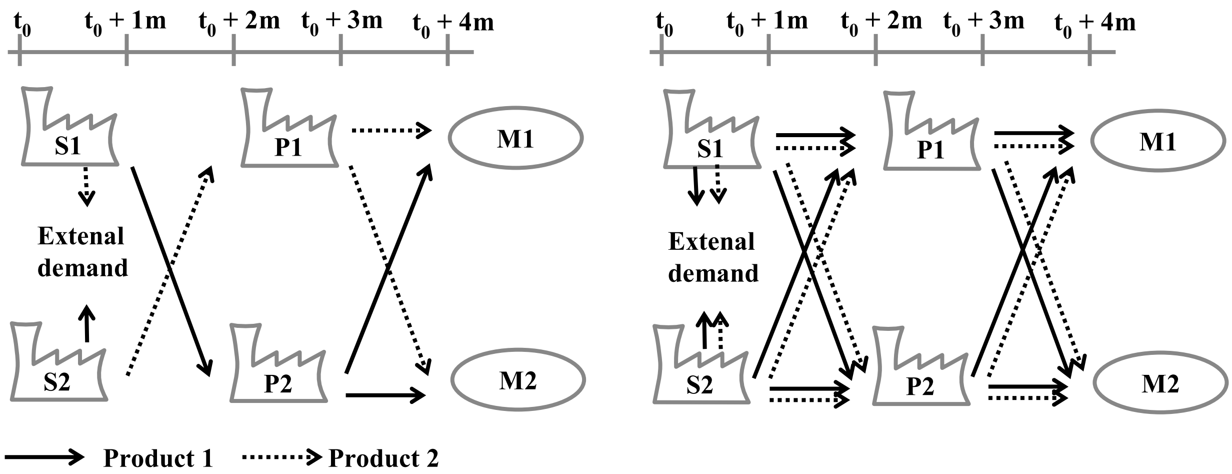
The technology cost associated with the implementation of new IT is often underestimated. According to Brynjolfsson, for each dollar spent on ERP systems such as “SAP’s R/3 […] typically three or four dollars are spent on consultants who implement the system” (Brynjolfsson 1998, p. 55). Annual maintenance fees oscillate among 10 % to 20 % of the purchase cost and internal resources for data processing and up-dating are important (Brown 2006). The quality of planning results (complementary to autonomy cost) usually is measured by total transportation, production and holding cost as well as lost benefits in case of backlogging. Organization cost is the sum of expenses for employees related to the execution of coordination activities. While technology cost is relatively easy to assess, autonomy and organization cost is difficult to quantify. Autonomy cost depends to a large extent on uncertainties so that simulation techniques are required for their estimation. Organization cost can be split into two parts. Fix cost have to be incurred for major changes in the organization, i.e. techno-structure, support staff, liaison devices, SOP etc. The implementation of a central coordination unit means a major change in the organization structure in case of horizontal consolidated and fully integrated organizations. The vertically segmented form can be managed by a lead SC coordinator in each segment. The variable cost for SC coordination depends on the complexity of the tasks, i.e. on the activity level of the employees. From a static point of view coordination tasks are getting more complex with increasing number of coordination objects (e.g. machines, products). Additionally dynamic factors influence significantly the complexity. For example high capacity loads or volatile lead time result in higher probabilities for re-planning. The cost estimation requires simulation due to the dynamic properties.

6. Simulation model

The simulation model represents the coordination and the material flow layer. Both sub-models interact periodically. The software package (*Plant Simulation*) was selected because of its object oriented concept of inheritance and the powerful built-in programming language *SimTalk*. Hence, alternative organization forms can be derived using basing module and coordination mechanism can be programmed (Zapata et al. 2007).

Figure 3 illustrates the material flow configurations for the different organization forms.

Figure 3. Material flows for fragmented or vertically segmented (left) and horizontally consolidated or fully



integrated (right) organization forms

For the sake of simplicity all production and supply lead times equal one month, therefore latest start date of the first production process is t_0 for delivery in t_0 + 4 month.

Two products are sold in both markets. Mean demand is 10.000 units/month for each product in each market. However, demands are uncertain. We consider that demands can be represented by the normally distributed function with a standard deviation of 1.000 units/month. Furthermore, locations S1 and S2 supply semi-finished goods to external partners. We assume that the total sum is 500 units/month (normally distributed at 10 %

standard deviation). The planning horizon is four month – that equals the total lead time from production start at the first facility to customer delivery. Finished products demands are forecasted each month incurring forecast errors of 20 % for the fourth, 15 % for the third, 10 % for the second and 5 % for the first month. All material flow decisions are taken based on these uncertain quantities. The plant capacities are determined so that at mean demand still 5% capacity reserve is available in order to absorb some demand volatility.

Table 2 summarizes the cost parameters chosen for the case study. Note that only for the horizontally consolidated and the fully integrated form the entire set of material flows is allowed. The selection of material flows for fragmented and vertically segmented organization is cost minimal for the chosen parameters and the capacity restrictions. The yearly holding cost is estimated at 10 % of the cost of goods. Margins vary depend on the facilities chosen to manufacture the products. Sales prices are determined to be 2 € above the highest supply chain of each product-market combination.

Table 2. Organization forms, dependencies and IT solutions

Production unit cost (cm_i^k) in €/unit			Transportation unit cost ($cs^{k',k}$) from k′ to k in €/unit				
	Product i			Location k			
location k	1	2	Location k′	P1	P2	M1	M2
P1	10	4	S1	5	8		
P2	6	3	S2	3	6		
S1	2	2	P1			4	5
S2	4	3	P2			10	8

According to the ERP logic, production and delivery dates and quantities are determined based on net requirements. Each market demand for a product should be satisfied by the lowest cost facility or internal supply chain. However, if capacity or material conflicts arise, either production might be anticipated to earlier periods (leading to additional holding cost) or orders have to be allocated to alternative facilities or supply chains. The latter case obviously is not applicable to all organization forms.

Table 3. Cost parameters for supply chain configurations

Supply (ID)	1	2	1	2	2	1	2	1	1	2	2	2	1	1	2	1
Production (ID)	1	1	1	1	2	1	1	2	1	1	2	2	2	2	2	2
Market (ID)	1	1	2	2	2	1	1	2	2	2	1	2	1	2	1	1
Product (ID)	2	2	2	2	2	1	1	2	1	1	2	1	2	1	1	1
Cost (€/Unit)	**15**	**15**	**16**	**16**	**20**	**21**	**21**	**21**	**22**	**22**	**22**	**23**	**23**	**24**	**25**	**26**

Table 3 summarizes the unit costs summed up for transportation and production. Note that for the same product-market demand alternatives exist that are indifferent with respect to unit cost. Consequently in case of cost parity alternative routing is preferred to holding cost. In all other cases anticipated production is the more economic solution given that holding cost are relatively low. The decision which product-market combination will be assigned firstly to free capacities is coordinated depends on the IT system. If no APS is used simple heuristic rules are applied. In the current case study the product-market demand with the lowest total cost is assigned firstly. For optimal results optimization algorithms are necessary. Given that only four different product-market demands exist, all possible combinations are tested at each coordination time point in order to reproduce APS functionality. The solution that delivers the lowest overall network cost is selected out of all alternatives.

Table 4 summarizes the simulation results. The fragmented and vertically segmented form basically lead to lower margins because demands can not be satisfied by alternative locations. The decision to centralize the ERP system should be based on the coordination cost. The simulation study revealed that in 43 % of all cases, iterative coordination procedures among facilities are necessary. The associated cost (human resources) has to be compared with the expenses for the ERP integration project. An increase of approximately 0.2 m€ per year can be achieved by means of horizontally consolidated coordination. If an APS system is implemented margins can be further augmented by 0.2 m€ per year – then technology investment and reduction in headcount has to be considered too.

Table 4. Simulation results

Fragmented	**Vertically segmented**	**Horizontally consolidated**	**Fully integrated**
Sales per year			
10.25 m€	10.25 m€	12.24 m€	12.24 m€
Yearly transportation, production and holding cost			
7.94 m€	7.94 m€	9.67 m€	9.51 m€
Margins per year			
2.31 m€	2.31 m€	2.56 m€	2.73 m€

7. Conclusions

In this investigation discrete event simulation has been applied to quantify the logistic performance improvements from different organization forms. Additionally, the underlying coordination mechanisms and IT instruments have been described. As expected the fully integrated centralized organization supported by APS system achieves the best result. However, partially centralized forms require less investment in technology and ERP systems inherent coordination mechanisms cover basic dependencies. In the current study only one set of network configurations and parameters have been tested. Future research should focus on how variations in the experiment set-up influence the evaluation of organization forms.

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