From Theory to Practice: The Impact of 3D Printing on Supply Chain Configurations and Cost Efficiency – A Case Study from Germany

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Abstract
Additive manufacturing (AM) or 3D printing (3DP) has been considered as revolutionary in terms of manufacturing and its impact on supply chain configurations This paper attempts to investigate the economic and environmental benefits of using 3D Printing (3DP) technology through constructing two scenarios for the location of 3DPs, namely a centralized and a discrete decentralized 3DP locations, taking into consideration different number of printers at different number of warehouses and/or different number of stores. The paper studies these scenarios from the perspective of a spare parts retailer, using the hazard button with relevant empirical data, as a real-life case study. A linear programming model has been developed, with an objective function setup to minimize total costs, that is broken down into transportation, inventory, overhead, labour and production costs, as well as the quantity of 3DPs deployed across different locations. The model thus, functions as a decision-making tool for stakeholders in determining the optimal placement of 3DP resources within the supply chain. The study concludes by demonstrating tipping points where 3DP deployment decisions shift between different configurations. Notably, labour costs significantly influence decision-making, particularly in high-wage countries like Germany.

Keywords
3D printers, linear programming, distribution networks, automotive industry, sustainability.

Introduction
3D Printing (3DP) also known as additive manufacturing (AM) has been lately discussed in academic and professional settings and hailed as a disruptive technology (Halassi, Semeijn, and Kiratli 2019). This technology uses the concept of manufacturing parts one layer at a time, contrary to subtractive methods such as milling and drilling where a block of material is reduced to the required final shape through automated control of machines also known as Computer Numerical Control (CNC) (Khajavi, Partanen, and Holmström 2014).
Furthermore, 3DP allows for different benefits that were not attainable before such as the production of complex designs, less production waste, democratization of manufacturing by allowing users to have an easily accessible production tool to print their needs with less complications and at cheaper costs. Moreover, 3DP allows for the shift of production locations across the supply chain, allowing the shortening of the supply chains and hence lowering lead times, on-demand and in-situ production as well as centralized (at central locations and/or hubs) and decentralized distributed -near customers- production (Liu et al. 2014; Xu, Rodgers, and Guo 2021).

In this paper we introduce a mathematical model comparing the placement of 3DP at different locations in the supply chain, namely comparing between the cost performance of centralized (and decentralized 3DP configurations by grounding a case of an automobile spare parts manufacturer in Germany taking the danger (hazard) button as printing part. We assume the warehousing locations as the centralized (CE) 3DP locations, while on the other hand, we use the main stores in the cities served by the company as locations for the decentralized (also known as discrete DI) 3DP manufacturing. We expand this calculation to test for a combination of different numbers of printers and locations, observing the tipping points and boundaries of which system is cost efficient.

Objective
The objective is to examine an alternative solution to the current supply chain. Accordingly, we developed a mathematical model that analyses cost efficiency by examining two main variables. The first variable is the deployment location (CE and DI) of the 3DP within the supply chain network, the second variable is the number of printers at each location. Thus, providing a tool for stakeholders to better their logistics related decision making.

Literature Review and Research gap
Several studies have investigated the deployment of 3DP in different locations (centralized and decentralized) for spare parts supply chains using different methodologies, in their study Li et al. (2018) have used a simulation methodology to compare different supply chain configuration for homogenous demand with make to order and make to stock production policies. Khajavi et al (2014) used scenario modelling to test different configurations where total operating costs is used for the comparison, they have concluded that while a centralized configuration was still preferable, they have noted that a decentralized configuration would be a viable option when the 3D Printer investment costs become cheaper and more autonomous. Roca et al. (2019) suggested that shifting from a centralized to a localized manufacturing is not yet practical and only feasible for higher volumes “tens of thousands”.
Furthermore, Rinaldi et al. (2021) have conducted a supply chain (SC) performance evaluation for different SC configurations with traditional and 3DP deployments, they concluded that 3DP allows for cost efficient shorter SCs in

terms of savings and lead time, in addition, the deployment of 3DP in a decentralized networks provides higher customer satisfaction and lower SC costs.

In (Xu, Rodgers, and Guo 2021), the authors devised a scenario based analysis of three different configurations, namely: centralized, distributed and hub configuration, whereby, a centralized is identified as one central 3DP location, decentralized 3DP facilities where deployed at the end of the chain, and hubs are deployed as a middle ground. In their first scenario, a hub system provided the least lead time and least cost per order.

On the other hand, we identify the research gap that focus on the relation between number of warehouses (centralized locations) and number of stores (decentralized distributed locations) as well as the effect of deploying multiple printers across different supply chain configurations.

Methods

This section explains the linear programming model assumptions, model construction and input variables, furthermore, we take explain the case study of the focal company and the outcome of solving the algorithm.

Model assumptions

The following assumptions are made to simplify the problem and facilitate model solving.

1.The price of the shop is the area used times the average monthly rent per square meter of the local warehouse, without taking the limitations of the market rental area into account, the area required in the calculation process is the area of the space rented.

2. No downtime or material disconnection during AM operation.

3. The demand for parts is equal to the supply and the maximum output of the printer.

4. The depreciation cost of the AM printer is not considered.

5. Each store has a certain amount of inventory at the beginning of the period, i.e., it is exempt from the AM production waiting time at the beginning of the period.

6. The pallets mentioned in this article are all European standard pallets, with dimensions of 1.2*0.8m, for safety and general shelf height considerations, a pallet height of 1.8m. The volume of the package is 0.15m*0.15m*0.3m.

Variable settings

Table 1. Variables settings and notations.

Notation	Explanation	Notation	Explanation
$C_{machine}$	AM machine acquisition cost in €/unit	C_{electr}	cost of electricity in €/year
$M_{materia}$	each unit required Material in kg	C_{labour}	Employee training cost in €
C_{roll}	Price of printing material in €/kg	c	quantity of warehouse
C_{rent}	Unit rent €/m^2 per year in €	d	quantity of stores
N	Maximum quantity of units per print in units/day	X	quantity of printers in warehouse
D_{work}	Number of working days per year	Y	quantity of printers in stores
C_{PAL_t}	Logistics price of pallets for the month in €/month	C_{pal_a}	average price of pallets in €/year

S_{shop}	Store area for computer and operation space in m^2	$C_{rent_{w-a}}$	average unit rent in warehouse€/m^2 per year in €
$S_{storage}$	Storage area for product and pallet in m^2	$C_{rent_{s-a}}$	average unit rent in shop €/m^2 per year in €
C_{part}	Acquisition cost of rubber gaskets and electronic chips in €/unit		

Model construction

Total material cost including accessories in each shop €/year

$$Z_{material} = (M_{material} * C_{roll} + C_{part}) * N * D_{work} \quad (1)$$

Total cost of electricity in each shop €/year $Z_{electr} = C_{electr}$ (2)

Total rent in each shop €/year $Z_{rent} = (S_{shop} + X) * C_{rent}$ (3)

AM machine acquisition cost in each shop €/year $Z_{machine} = C_{machine}$ (4)

Employee training cost in each shop €/year $Z_{labour} = C_{labour}$ (5)

Therefore, the cost objective function of AM in each shop is:

$$Z_{AM} = Z_{rent} + Z_{machine} + Z_{material} + Z_{electr} + Z_{labour} \quad (6)$$

To control the variables, the total quantity of both production models is set in this paper as, the maximum production quantity of CE AM production for one year, i.e. N_{new} =cN (7)

Total material cost including accessories €/year

$$Z_{material-CE} = Z_{material-DI} = (M_{material} * C_{roll} + C_{part}) * cN * D_{work} \quad (8)$$

Total cost of electricity €/year $Z_{electr-CE} = Z_{electr-DI} = c \sum C_{electr}$ (9)

AM machine acquisition cost

$$Z_{machine-CE} = c * X * C_{machine} \quad (10)$$

$$Z_{machine-DI} = d * Y * C_{machine} \quad (11)$$

Employee training costs

$$Z_{labour-CE} = cC_{labour} \quad (12)$$

$$Z_{labour-DI} = dC_{labour} \quad (13)$$

Total logistics price €

$$Z_{trans-CE} = c * \sum C_{PAL\_t} \ (t = 1,2, \dots 12) \quad (14)$$

$$Z_{trans-DI} = 0 \quad (15)$$

Total rent €/year

$$Z_{rent-CE} = \sum_{c=1}^{C} Crent - w * (S_{stroge+}S_{shop} + X) + \sum_{d=1}^{D} Crent - s * S_{shop} \quad (16)$$

$$Z_{\text{rent-DI}} = \sum_{d=1}^{D} Crent - s * (S_{shop} + Y) \quad (17)$$

total cost difference between decentralized and centralized production

$$D = Z_{CE} - Z_{DI} \quad 18)$$

$$= \text{c} * \sum \text{C}_{\text{PAL}_{-\text{t}}} + \sum_{\text{c}=1}^{\text{C}} \text{Crent} - \text{w} * \left(S_{stroge+}S_{shop} + X\right) - \sum_{d=1}^{D} Crent - s * Y + (c\text{X} - d\text{Y})C_{machine} + (c-d)\text{C}_{\text{labour}} \quad (19)$$

When take the logistics and warehousing costs around the arithmetic average, equation (19) can be transformed to analyse the cost difference with the relationship between warehouse and the number of stores:

$$= c * C_{pal_a} + c * \text{C}_{rent_{w-a}} * \left(S_{stroge+}S_{shop} + X\right) - d * C_{rent_{s-a}} * Y + (c\text{X} - d\text{Y})C_{machine} + (c-d)\text{C}_{\text{labour}} \quad (20)$$

Table 2. Variable inputs

$C_{machine}$	3D printer price	200	€
C_{roll}	PLA printing material prices	22	€/kg
C_{part}	Unprintable parts rubber gaskets and electronic chips sourcing costs and packaging	1.5	€/Unit
N	Maximum number of complete parts printed per plane at a time	13	Units
$M_{material}$	Each unit required Material	0.013	kg
D_{work}	Working days	230	Days
C_{labour}	Employee training costs	4000	€
S_{shop}	Store area for computer and operation space	2	m²
$S_{storage}$	Storage area for product and pallet	2	m²
c	quantity of warehouse	2	-
d	quantity of stores	7	-

Table 3. Transportation, electricity and rent costs from warehouses to stores.

C_{trans}				C_{electr}	C_{rent}
From Warehouse	To shop	cost/pallet	cost/year		
Berlin	-	-	-	504.3	122.64
	Berlin	76.61	919.32		
	Hamburg	74.71	896.52	557.24	135.96
	Leipzig	68.68	824.16	524.83	70.32
Gelsenkirchen	-	-	-	533.25	115.2
	Cologne	70.72	848.64	553.04	129.6
	Stuttgart	80.98	971.76	496.12	158.52
	Frankfurt	77.2	926.4	504.15	150.96
	Munich	88.99	1067.88	503.17	182.04
Average price		-	922.10	-	118.92(warehouse) 135.72(shop)

Case study

Company F, manufacturer of automobile spare parts owns a manufacturing facility located in Ennepetal, Germany with two warehouses in Berlin and Gelsenkirchen used in this case as the centralized 3DP locations. Seven cities are selected as the main stores served by the company as locations for the decentralized calculation. Without considering the temporary redeployment of insufficient warehousing, seven cities can be matched with two warehouses according to the transport costs and distances between the warehouses and the cities (figure 1). In this paper, we take the danger button as our base of calculation. Based on the information obtained from the research and literature, the corresponding parameter values were derived.

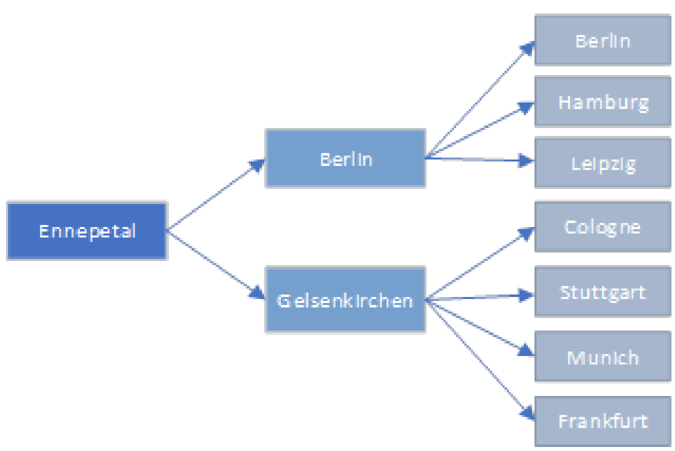

Figure 1 . Company F supply chain

Table 4. Costs in each AM shop.

Each shop	Berlin	Hamburg	Leipzig	Cologne	Stuttgart	Munich	Frankfurt	Sum	%
$Z_{material}$	5340.14	5340.14	5340.1	5340.14	5340.14	5340.14	5340.14	37381	51%
Z_{electr}	504.3	557.24	524.83	553.04	496.12	503.17	504.15	3642.85	5%
$Z_{machine}$	200	200	200	200	200	200	200	1400	2%
Z_{labour}	4000	4000	4000	4000	4000	4000	4000	28000	38%
Z_{rent}	367.92	407.88	210.96	388.8	475.56	546.12	452.88	2850.12	4%
Z_{trans}	0	0	0	0	0	0	0	0	0%
Z	10412.36	10505.3	10276	10482	10511.8	10589.43	10497.17	73274	100%

Table 5. Costs of using decentralized production.

DI	Berlin	Hamburg	Leipzig	Cologne	Stuttgart	Munich	Frankfurt	Sum	%
$Z_{material}$	total material cost equal CE model							10680.3	24%
Z_{electr}	total electricty cost equal CE model							1037.55	2%
Zmachine-DI	200	200	200	200	200	200	200	1400	3%
Zlabour	4000	4000	4000	4000	4000	4000	4000	28000	64%
Z_{rent}	367.92	407.88	210.96	388.8	475.56	546.12	452.88	2850.12	6%
Ztrans	0	0	0	0	0	0	0	0	0%
Z	-							43968	100%

Table 6. The costs of using centralized production.

CE	Warehouse		Shop							sum	%
	Bln.	Gek.	Bln.	Hbg.	Lej.	Cgn.	Str.	Muc.	Fra.		
$Z_{material}$	5340.14	5340.14	0	0	0	0	0	0	0	10680.28	30%
Z_{electr}	504.3	533.25	0	0	0	0	0	0	0	1037.55	3%
$Z_{machine}$	200	200	0	0	0	0	0	0	0	400	1%

Solving the algorithm

From Table 4 we can conclude that, when the AM printer in each store reaches its maximum capacity, the cost of materials accounts for the largest share of all expenses, at over 50%. In second place is the cost of personnel training, which accounts for 38%. Machine costs and rent account on the other hand are only a small percentage.
As mentioned earlier, to better compare the differences between the centralized AM machine setup and the decentralized AM setup, the total order quantity of both production models is set in this paper as, the maximum production quantity of centralized AM production for one year. Under this assumption, the results are shown in Table 5&6.

From the previous tables, we can conclude that: because of the control variables, material costs and energy costs are not meaningful for comparison in the two models. The cost of rent is a relatively small percentage of the total cost (<10%), and the cost of machine acquisition is negligible (1% & 3%) compared to other items in the total cost. Personnel training costs are relatively large in both models, 64% in the DI case, being the most significant share of expenses. While on the other hand, it is 22% in the CE case, being the third largest share of expenses. The first share of expenses in the CE case is transportation costs, while in the DI case, this expense is completely absent as parts are printed in the stores and no delivery is required from the previous step in the chain.

From a sustainability perspective, we can look at the two scenarios from a social lens and simultaneously from an environmental lens. From a social viewpoint, both scenarios consider personnel training offering employees a transferable skillset. From an environmental viewpoint, the model also looks at transportation which can be further

translated into emissions and compared across both scenarios. In other words, even though the equations have been modelled mainly around costs, social and environmental impacts can also be inferred.
Further analysis of the total cost in both cases can be analysed through the cost differences between the two scenarios. The cost difference between using centralized AM production and decentralized AM production in the case of this arithmetic example is D_{CE-DI}=36116.47-43967.95=-7851.48 €, i.e., centralized production costs 7851.48 € less than decentralized. When substituting the example data in (20), the relationship between the cost difference between CE & DI production and the number of warehouses and stores in the example can be obtained.

$$D = 5397.78c + 318.92cX - 335.72dY - 4000d \quad (21)$$

When the number of the AM printer per warehouse and per store (in other words per location where the printer needs to be set) is 1 in both models, that is, when x=1, and y=1, the following function between quantity of warehouse and stores as independent variables and cost differences can be obtained as (22).

$$D = 5716.7c - 4335.72d \quad (22)$$

When D = 0, that is, the total cost of CE AM production and DI AM production is the same. We reach in this case the critical value of the cost advantage of decentralized AM production.

Table 7 shows the total cost variance as affected by the number of warehouses and stores. We can see here the boundaries of when it is cost efficient when we have c number of warehouse, and d number of stores in this specific case study. We propose here a concept of tipping points, where the placement of the 3DP is dependent on the difference in total cost between number of warehouses compared to the total cost of number of stores. In other words, as per seen in table 7 above, the highlighted values in green signify a higher cost in the warehouses, therefore, it is more efficient to position 3DPs in stores i.e., decentralization. Conversely, the highlighted values in red signify a higher cost in the stores, therefore it is more efficient to position 3DPs in warehouse, i.e., centralization.

Moreover, we take equation 21, and input c=2 and d=7, i.e., when the number of warehouses is 2 and the number of stores is 7, leading to the following functional relationship between the number of machines and the total cost variance.

$$D = 637.84X - 2350.04Y - 17204.44 \quad (23)$$

As seen from table 8, it becomes quite clear that the number of printers does not have much impact on the decision of where the printers should be placed. As can be seen, it is only after adding 31 printers at each warehouse does it become more feasible to decentralize. This signifies how much of an impact labour cost has on the model in comparison to transportation costs.

Table 7. Warehouse -Store cost difference table

	number of warehouses (c)								
number of stores (d)	0	1	2	3	4	5	6	7	8
0	0.00	5716.70	11433.40	17150.10	22866.80	28583.5	34300.2	40016.9	45733.6
1	-4335.72	1380.98	7097.68	12814.38	18531.08	24247.78	29964.48	35681.18	41397.88
2	-8671.44	-2954.74	2761.96	8478.66	14195.36	19912.06	25628.76	31345.46	37062.16
3	-13007.16	-7290.46	-1573.76	4142.94	9859.64	15576.34	21293.04	27009.74	32726.44
4	-17342.88	-11626.18	-5909.48	-192.78	5523.92	11240.62	16957.32	22674.02	28390.72
5	-21678.60	-15961.90	-10245.20	-4528.50	1188.20	6904.9	12621.6	18338.3	24055
6	-26014.32	-20297.62	-14580.92	-8864.22	-3147.52	2569.18	8285.88	14002.58	19719.28
7	-30350.04	-24633.34	-18916.64	-13199.94	-7483.24	-1766.54	3950.16	9666.86	15383.56
8	-34685.76	-28969.06	-23252.36	-17535.66	-11818.96	-6102.26	-385.56	5331.14	11047.84
9	-39021.48	-33304.78	-27588.08	-21871.38	-16154.68	-10438	-4721.28	995.42	6712.12
10	-43357.20	-37640.50	-31923.80	-26207.10	-20490.40	-14773.7	-9057	-3340.3	2376.4
11	-47692.92	-41976.22	-36259.52	-30542.82	-24826.12	-19109.4	-13392.7	-7676.02	-1959.32
12	-52028.64	-46311.94	-40595.24	-34878.54	-29161.84	-23445.1	-17728.4	-12011.7	-6295.04
13	-56364.36	-50647.66	-44930.96	-39214.26	-33497.56	-27780.9	-22064.2	-16347.5	-10630.8
14	-60700.08	-54983.38	-49266.68	-43549.98	-37833.28	-32116.6	-26399.9	-20683.2	-14966.5
15	-65035.80	-59319.10	-53602.40	-47885.70	-42169.00	-36452.3	-30735.6	-25018.9	-19302.2
16	-69371.52	-63654.82	-57938.12	-52221.42	-46504.72	-40788	-35071.3	-29354.6	-23637.9

Table 8. Cost of deploying printers x at warehouses, and y printers at stores.

	Number of printer x at warehouses								
number of printers y at stores	24	25	26	27	28	29	30	31	32
0	-1896.28	-1258.44	-620.6	17.24	655.08	1292.92	1930.76	2568.6	3206.44
1	-4246.32	-3608.48	-2970.64	-2332.8	-1694.96	-1057.12	-419.28	218.56	856.4
2	-6596.36	-5958.52	-5320.68	-4682.84	-4045	-3407.16	-2769.32	-2131.48	-1493.64
3	-8946.4	-8308.56	-7670.72	-7032.88	-6395.04	-5757.2	-5119.36	-4481.52	-3843.68
4	-11296.4	-10658.6	-10020.8	-9382.92	-8745.08	-8107.24	-7469.4	-6831.56	-6193.72
5	-13646.5	-13008.6	-12370.8	-11733	-11095.1	-10457.3	-9819.44	-9181.6	-8543.76
6	-15996.5	-15358.7	-14720.8	-14083	-13445.2	-12807.3	-12169.5	-11531.6	-10893.8
7	-18346.6	-17708.7	-17070.9	-16433	-15795.2	-15157.4	-14519.5	-13881.7	-13243.8
8	-20696.6	-20058.8	-19420.9	-18783.1	-18145.2	-17507.4	-16869.6	-16231.7	-15593.9
9	-23046.6	-22408.8	-21771	-21133.1	-20495.3	-19857.4	-19219.6	-18581.8	-17943.9
10	-25396.7	-24758.8	-24121	-23483.2	-22845.3	-22207.5	-21569.6	-20931.8	-20294
11	-27746.7	-27108.9	-26471	-25833.2	-25195.4	-24557.5	-23919.7	-23281.8	-22644
12	-30096.8	-29458.9	-28821.1	-28183.2	-27545.4	-26907.6	-26269.7	-25631.9	-24994
13	-32446.8	-31809	-31171.1	-30533.3	-29895.4	-29257.6	-28619.8	-27981.9	-27344.1
14	-34796.8	-34159	-33521.2	-32883.3	-32245.5	-31607.6	-30969.8	-30332	-29694.1
15	-37146.9	-36509	-35871.2	-35233.4	-34595.5	-33957.7	-33319.8	-32682	-32044.2

Conclusion

Our results illustrate that while deploying 3DP(s) allow for different supply chain configurations, it is not a binary choice between one configuration and the other, rather, it depends on the number of facilities where the 3DP(s) are deployed and thus identifying the point where the decision tips from one configuration to the other. Additionally, in our case, the number of printers deployed have a negligible effect on the configuration.

Furthermore, since this case study has been conducted in Germany, which is known to have a high minimum wage, and based on our assumption that each printer requires an operating personal, this has led to a labour cost having a significant impact on the 3DP positioning within the supply chain model. Alternatively, if a similar case was to be conducted in a country with lower labour and transportation costs, this might possibly have an impact on the decision. To demonstrate a deeper understanding of the research challenge, we recommend the replicability of our model, through different scenario analysis, where variables such as labour costs, 3D printing costs and transportation costs could be modified within plausible ranges for further analysis. We also recommend the study of carbon footprint of both models as an environmental factor in the sustainability performance.

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Biographies

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