QUANTITATIVE NETWORK DESIGN ANALYSIS IN A MULTIMODAL TRANSPORTATION COMPANY SERVING THE ADDITIVE MANUFACTURING INDUSTRY

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The current research presents quantitative data and communication network design analysis for an international multimodal transportation company. The proposed communication network is considered as a hierarchical organization from the additive manufacturing sector. The authors define the main management levels, the information transfer nodes and the direction of data displacement and design the general structure of the network using oriented graphs. For the quantitative analysis, centrality evaluation indicators are used. It is concluded that the degree of proximity decreased proportionally with the number of nodes between any two members of the communication network.

Keywords: data and communication network design, quantitative analysis, information system, additive manufacturing supply chain

1. Introduction

In recent years the Additive Manufacturing (AM) industry has experienced on-going growth. According to T. Wohlers [1] the global market AM products and service grew in 2012 to over $2billion, with an estimate of 29% CAGR (compound annual growth rate). In 2012 unit sales of professional-grade, industrial systems reached nearly 8,000 units, registering an increase of almost 23% from an estimated 6,500 units in 2011 [1, 2]. This growth excludes the sales of personal 3D printers that sell for under $5,000 [1]. This demonstrates a growth trend of industrial AM systems sales worldwide. The worldwide projected value in the AM and 3D printing industry is of $4billion in 2015, $6billion in 2017 and of $10.8billion in 2021 [1, 2]. Current AM applications range from automotive, aerospace, medical, architecture, military and defense, education and training, all the way to nano-manufacturing, biomedical implants and in-situ bio-manufacturing [1-4]. According to the Royal Academy of Engineering [2] a potential application in 2032 is full body organs printing.

As this technology becomes available to the ordinary consumer the need arises for specialized regulations to be developed, in order to address some real concerns:

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intellectual property safety, policy compliance, economic equity and human right compliance [5]. Many companies are starting to incorporate AM into their supply chain due to its ability to impact inventory and distribution [2,3,4,6]. Classic supply chain management solutions do not apply to the AM industry due to its unique characteristics [7, 8, 9]. Planning and logistics need to target the specifics of these technologies [8, 9].

Considering the aforementioned, various implications (amongst national security and safety) need to be taken into account when designing a data and communication network for an international company that transports AM products and services. Thusly, the paper proposes a quantitative analysis of a data and communication network for a transportation and distribution company that operates within the AM sector. The company started as a spin-off and was initially set up to ensure that AM specific regulations, standards and legal issues are met. The main activity domain is transportation and distribution of AM goods and services. It also specializes in legal consultancy and standardization of international commercialized AM products. Within the following, the international transportation and commercialization company will be referred to as InterTransAM Inc. (ITAM).

2. Quantitative analysis using network theory

InterTransAM Inc. provides international intermodal transportation and commercialization for the following goods and services destined for the AM industry: Industrial and personal use equipment; Maintenance and service; Materials; Spare parts; Customized parts; Series parts; Technical support for industrial and research applications; Training and teaching; Software; In-process quality assurance, monitoring & control; Certification; Methodology & standards compliance; Disposal/ recycling service. The company has its own fleet comprised of a private jet airline, truck and naval fleet and a freight train. ITAM has collaboration partnerships with twelve different system and material manufacturers from the AM sector located in Europe, U.S., China, Israel and Japan. The main headquarters of InterTransAM Inc. is situated in the United States and has sixteen different regional offices, amongst which five are within the U.S. and the rest are in central Europe and Israel. The authors define the main management levels, the information transfer nodes, data displacement and design the general structure of the network using graphs (Fig.1).

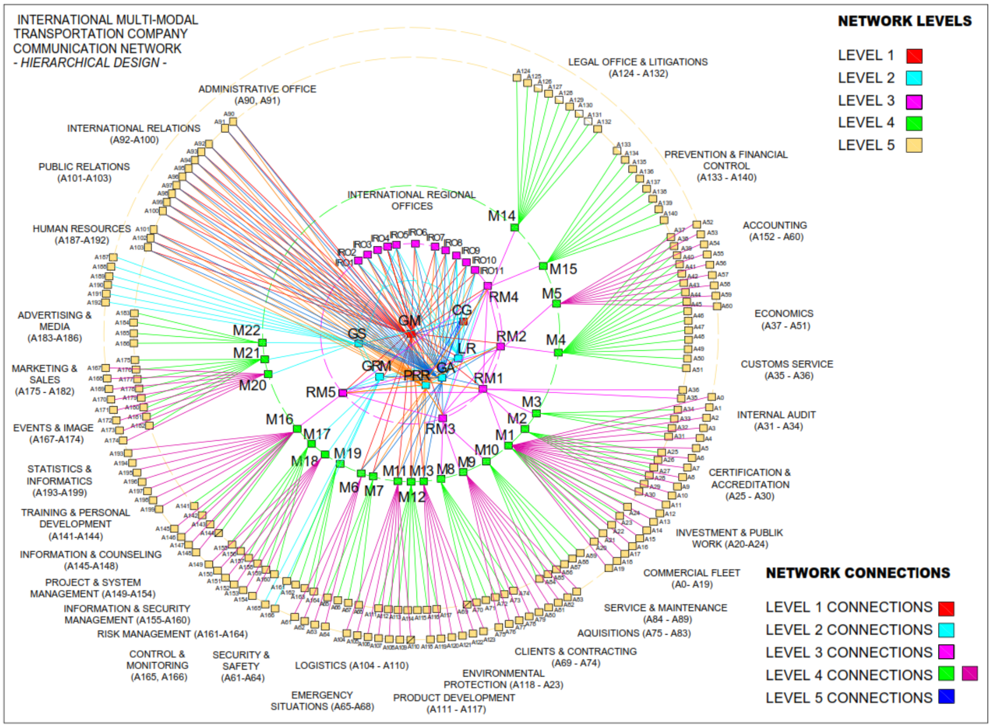

Fig. 1. The communication network design of ITAM headquarters

The notations used to construct the communication and data network are as follows: GM – General Manager; PRR – Public Relations Representative; GA – General Administrator; LR(2) – Legal Representative (two persons); GS – General Secretary; GRM – General Risk Manager; GC – General Counsellor; IRO1÷IRO11 – International Regional Offices; RM1÷RM5 – Regional Managers (national offices); M1÷M22 – Managers; A0÷A199 – Employees.

The ITAM organizational structure is represented as a descendent tree network with nodes and arches [11, 12]. The data and communication network is designed as a graph with five levels. A colour coding system was used to specifically identify the hierarchical levels and the connection types. The nodes are labelled according to the persons' position and are colour coded depending on their organizational level. The arches show the formal relations for the distribution of decisional information within the hierarchical organization.

The decision informational flow is unidirectional and moves from top to bottom [10, 11]. The data and communication flow takes place both top to bottom and bottom to top, but without creating loops within the network and eliminating redundant information and delay time [12].

In order to evaluate the decision power within the network, using the centrality evaluation indicators (CEI), a quantitative analysis was undertaken [10, 11, 13]. For the quantitative analysis, three CEI are used: the centrality degree, the proximity degree and the intermediation degree [8, 10, 13]. Each individual node is analysed in relation with all others from the entire network. The size and the international spread of the transportation company's facilities makes it a real challenge in designing an efficient and safe communication network for the AM specific regulations.

The centrality degree e_i is calculated for each individual node of the network with the following equation [7, 8]:

$$e_i = \frac{d_i}{N-1} \quad (1)$$

where, i – a member of the network;

d_i – no. of direct connections with other network members;

N – total no. of network members (i=1,...,N).

The proximity degree a_{ij} is calculated for each member i of the network, in correspondence with any other member j, with the following equation [7,8]:

$$a_{ij} = 1 - \frac{D_{ij} - 1}{D_{iM}} \quad (2)$$

where, D_{ij} – the shortest distance between node i and any other node j;

D_{iM} – the biggest D_{ij} distance.

The intermediation degree b_i is calculated on the premises that node i is on the shortest path between any other two nodes j and k [7, 8]:

$$b_i = \frac{N_i(j,k)}{N(j,k)} \quad (3)$$

where, $N_i(j,k)$ – the total no. of cases where node i is on the shortest path between any other two nodes j and k;

$N_i(j,k)$ – the total no. of (j, $k \neq i$) pairs between which there is a valid path.

3. Results and discussions

For the centrality degree two analyses are undertaken: for a 5 level network and for a 4 level network. The second analysis is deployed discarding the level 5 nodes for a more accurate centrality degree. An example of connection identification for nodes *GM* and *PRR* is shown in figure 2.

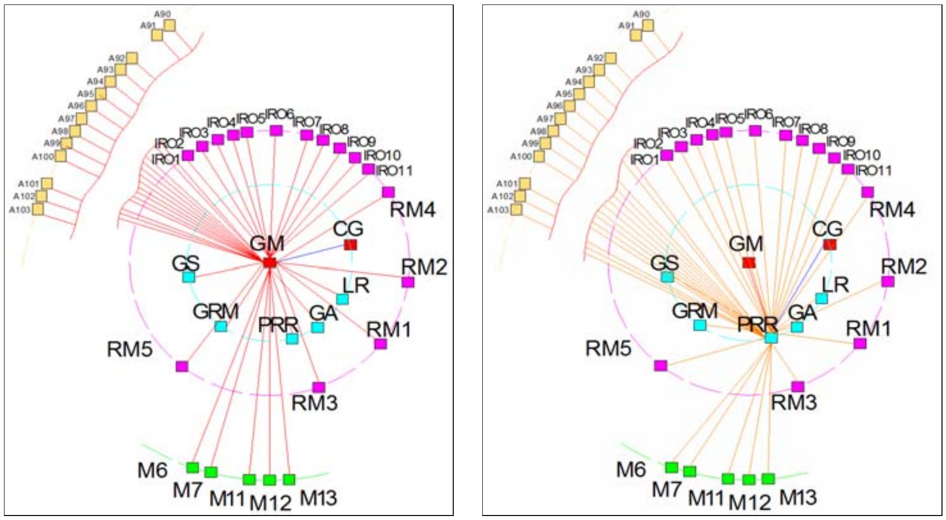

Fig. 2. Connections for nodes *GM, PRR* within the ITAM data & communication network

Using equation (1) the centrality was established for all the data and communication network nodes. The results of the analysis are synthesized in Table 1.

Table 1

Centrality degree for ITAM communication network

d_i	Analysis 1 245 connections	Analysis 2 45 connections	d_i	Analysis 1 245 connections	Analysis 2 45 connections
1	0.0041	0.0222	14	0.0572	-
3	0.0123	0.0667	15	0.0612	0.3333
5	0.0204	-	16	0.0653	0.3556
6	0.0245	0.1333	17	0.0694	-
7	0.0286	-	23	0.0939	0.5111
9	0.0367	-	26	0.1061	-
10	0.0408	0.2222	28	-	0.6222
11	0.0449	0.2444	42	0.1714	-
12	0.0490	0.2667			

The proximity degree is calculated for node *GM* in relation with all other nodes within the data and communication network using equation (2). In order to establish the maximum distances D_{ij} between two nodes, the following are considered: the information travels hierarchically from top to bottom, and cannot go any further down than the nodes in question; the information flow doesn't form loops. An example of identification of the minimum and maximum distances for node *GM* in relation with nodes *IRO5, RM5* and *M6* is shown in figure 3.

Applying relation (2) a proximity degree of *1* has been calculated between node *GM* and the following nodes: *PPR, GS, GA, LR, GRM, GC* and the international regional offices nodes.

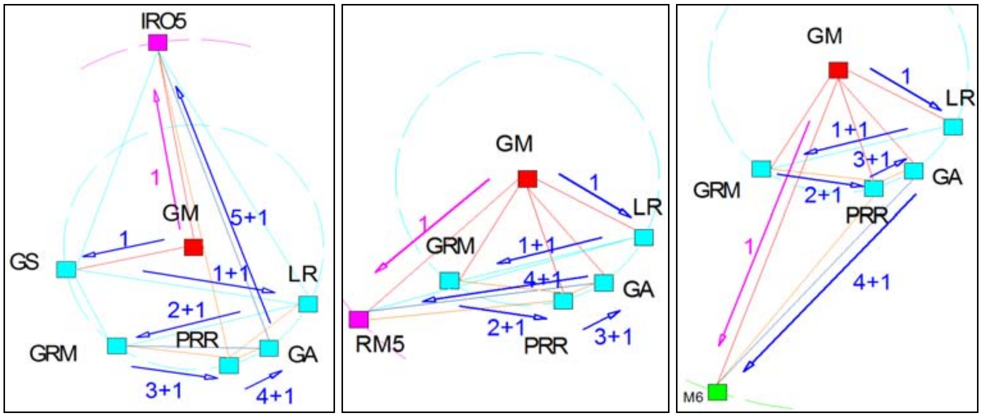

Fig. 3. Identification of the minimum and maximum distance between node *GM* and nodes: *IRO5, RM5* and *M6*

Applying relation (2) a proximity degree of *1* has been calculated between node *GM* and the following nodes: *PPR, GS, GA, LR, GRM, GC* and the international regional offices nodes.

Table 2

Proximity degree of node GM within the ITAM communication network

Nodes	$D_{GM,Ni}$	$D_{GM,M}$	$a_{GM,Ni}$	Nodes	$D_{GM,Ni}$	$D_{GM,M}$	$a_{GM,Ni}$
PPR, S, AP, LR, GRM, GC	1	5	1.0000	M1-M5, M8-M10, M14-M16	2	6	0.8333
RM1-RM5, M6, M7, M11-M13	1	5	1.0000	M17-M22	2	8	0.8750
Nodes	$D_{GM,Ai}$	$D_{GM,M}$	$a_{GM,Ai}$	**Nodes**	$D_{GM,Ai}$	$D_{GM,M}$	$a_{GM,Ai}$
A25-A30	3	7	0.7143	A104-A123	2	6	0.8333
A31-A34	3	7	0.7143	A124-A140	3	7	0.7143
A35-A36	2	6	0.8333	A141-A148	3	7	0.7143
A37-A51	3	7	0.7143	A149-A160	3	9	0.7778
A52-A60	3	7	0.7143	A161-A164	3	9	0.7778
A61-A64	2	6	0.8333	A165,A166	2	8	0.8750
A65-A68	2	6	0.8333	A167-A182	3	9	0.7778
A69-A74	3	7	0.7143	A183-A186	3	9	0.7778
A75-A83	3	7	0.7143	A187-A192	2	8	0.8750
A84-A89	3	7	0.7143	A193-A199	2	6	0.8333
A90-A103	1	1	1.0000				

According to [7] the intermediation degree is zero when node *i* has an extreme position within the network. Thusly, the intermediation degree is zero for *A0÷A199* nodes and the international regional offices nodes.

The intermediation degree for the nodes on level 4 of the communication network is calculated taking into consideration two hypotheses, stated as follows:

- If n is the total number of nodes within the communication network, $N(j,k)$ is calculated thusly:

$$N(j,k) = C_{n-1}^{2} + C_{n-2}^{2} + C_{n-3}^{2} + ... + C_{n-(n-2)}^{2} \Rightarrow \frac{1}{2!}\left[(n-1)(n-2) + (n-2)(n-3) + (n-3)(n-4) + ... + 2\cdot 1\right] \quad (4)$$

- If node i is of type M:

a) M_i is on the shortest way between any two A type subordinates, where $n_{A,Mi}$ – no. of A subordinates of M_i node:

$$N_p = \frac{n_{A,Mi}\cdot(n_{A,Mi}-1)}{2} \quad (5)$$

b) M_i is on the shortest way between any of its own A subordinates and any other A_n type subordinate on level 5, where n_A – total no. of type A employees, $n_{A,Mi}$ – total no. of type A subordinates of manger M_i:

$$N_p = (n_A - n_{A,Mi})\cdot n_{A,Mi} \quad (6)$$

c) M_i is on the shortest way between any of its own A subordinates and any other level 4 subordinate of type M_i, where n_{Mi} – total no. of M_i type employees, $n_{A,Mi}$ – total no. of A type employees subordinated to manager M_i:

$$N_p = n_{A,Mi}\cdot(n_{Mi}-1) \quad (7)$$

d) M_i is on the shortest way between any of its own A subordinates and any other level 3 subordinate of type RM_i, where n_{RMi} – total no. of RM_i type employees, $n_{A,Mi}$ – total no. of type A employees subordinated to manger M_i:

$$N_p = n_{A,Mi}\cdot(n_{RMi}-1) \quad (8)$$

e) M_i is on the shortest way between any of its own A subordinates and GC, LR, AP, PPR, GRM or GM:

$$N_p = n_{A,Mi}\cdot(GC + 2LR + GA + PRR + GRM + GM) = 7\cdot n_{A,Mi} \quad (9)$$

f) M_i is on the shortest way between any of its own A subordinates and IRO1 – IRO11:

$$N_p = n_{A,Mi}\cdot(IRO1 + IRO2 + ... + IRO11) = 11\cdot n_{A,Mi} \quad (10)$$

where, N_p – is the number of paths.

Thusly, the total no. of cases in which node M_i is on the shortes way between any other j,k pair – $N_{Mi}(j,k)$ – is calculated with the following equation:

$$N_{Mi}(j,k) = \frac{n_{A,Mi}\cdot(n_{A,Mi}-1)}{2} + (n_A - n_{A,Mi})\cdot n_{A,Mi} + n_{A,Mi}\cdot(n_{Mi}-1) + n_{A,Mi}\cdot(n_{RMi}-1) + 18\cdot n_{A,Mi} \quad (11)$$

Similarly, the intermediation degree for the RM_i nodes is established. The equation for the total no. of cases in which node RM_i is on the shortes way between any other *j,k* pair – $N_{Mi}(j,k)$ – is calculated with the following equation:

$$N_{RMi}(j,k) = (n_A - n_{A,RMi}) \cdot n_{A,RMi} + n_{A,RMi} \cdot (n_{Mi} - 1) + n_{A,RMi} \cdot (n_{RMi} - 1) + 18 \cdot n_{A,RMi} + \\ + \frac{n_{A,RMi} \cdot (n_{M,RMi} - 1)}{2} + (n_{Mi} - n_{M,RMi}) \cdot n_{M,RMi} + n_{M,RMi} \cdot (n_{RMi} - 1) + 18 \cdot n_{M,RMi} \quad (12)$$

The results are synthetized in table 3 and table 4 below.

Table 3

Intermediation degree for *Mi* nodes within ITAM communication network

Level 4 Nodes	*No of connections*	b_{Mi}	Level 4 Nodes	*No of connections*	b_{Mi}
M1	25	0.002346	M12	7	0.000683
M2	6	0.000586	M13	6	0.000586
M3	4	0.000393	M14	9	0.000874
M4	15	0.001438	M15	8	0.000778
M5	9	0.000874	M16	15	0.001438
M6	4	0.000393	M17	6	0.000586
M7	4	0.000393	M18	6	0.000586
M8	6	0.000586	M19	4	0.000393
M9	9	0.000874	M20	8	0.000778
M10	6	0.000586	M21	8	0.000778
M11	7	0.000683	M22	4	0.000393

It is concluded that the degree of proximity decreased proportionally with the number of nodes between any two members of the communication network. The analysis shows that the intermediation degree increases with the hierarchical level and the number of connections that each individual node has. Also, the centrality degree increased with almost 400% when level 5 of the network was discarded. Thusly, the authors propose a more compact structure of the network to facilitate the informational flow and the decision power. The solution is to merge levels 1 and 2 within a new top management level. Also, levels 2 and 3 need to merge and form the new second level within the hierarchical network.

Most businesses have three levels of management in place, according to Marcia J. Simmering in the Encyclopedia of Business, 2nd edition [14]. The current experimental results impose a condensed hierarchy of the ITAM data and communication network in order to clarify who has decision-making power and control, and who gives direction to whom.

Table 4

Intermediation degree for *RMi* nodes within ITAM communication network

Level 3 Nodes	Level 4 Nodes	*No of connections*	b_{RMi}
RM1	M1	25	0.003022
	M2	6	
	M3	4	
RM2	M4	15	0.002108
	M5	9	
RM3	M8	6	0.001878
	M9	9	
	M10	6	
RM4	M14	9	0.001546
	M15	8	
RM5	M16	15	0.001371

The network is simplified from a five level hierarchy to a three level one. Informational data is spread more evenly throughout the network and with less formal and structural barriers. The analysed solution generates speed in decision making since it reduces the hierarchy levels. Responsibility gets defined and clear to act. The decision making is clearer since it has not to be discussed and depends on general consensus. Thus, cascaded informational flow is avoided and the efficiency and productivity of the network is increased.

4. Conclusions

As more firms start to appreciate the potential benefits of AM across their supply chain and products, the transportation market dedicated to this specific sector is expected to grow significantly in the years to come. AM targeted transportation and distribution companies need to be as versatile and adaptable as the technology itself. This entails a complex and flexible organizational and informational structure, which is able to apply knowledgeable concepts and develop not only adaptable, but also interchangeable competences. A proper network design is the first step in achieving this goal.

The current paper presents research regarding the data and communication network design of an international multimodal transportation company that activates in the AM industry. A quantitative analysis was undertaken using the centrality evaluation indicators in order to determine the decision power within the studied network. The results show that the decisional and informational flow behaves within the normal trends, but within the lower limits of the CEI. In order to eliminate this discrepancy a second analysis was undertaken for the centrality degree. Based on the analysis, a more compact structure of the data and communication network was proposed. The restructuration of the network allows the information to reach all nodes faster, following shorter paths and eliminating intermediaries and lag time. Thusly, the company has the ability to react faster and knowledgeably to the environmental constant changes.

Further research entails a qualitative analysis of the data and communication network. A merger between different departments is also in plan.

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