Second Order Pareto Analysis [1]

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Abstract

Project delivery, particularly of large and complex infrastructure entails the engineering and implementation of a "solution" to an undesirable situation. Due to complexity, such a solution entails solving multi-dimensional problems (or aspects thereof); while the 'traditional' Pareto Analysis helps in prioritising the relevant problems or aspects, a 'systemic' approach shall prove more effective. Such an approach would also apply to quality improvements and risk management.

Second Order Pareto Analysis

In a recent publication (Mabelo, 2021), the author made the point that poor *understanding* of the problem to be solved may cause a project to fail (Haik and Shahin, 2011) and, thus, "Long before any design project starts, the design engineer has to believe that there is a problem that is worthy of their attention. The design engineer must feel a need [i.e., empathy] to solve the problem [...] must have a yearning to solve the problem [i.e., an undesirable situation]" (Slocum, 2008). However, decisions concerning the technical solutions to problems are often made by the designers themselves, who implicitly select "preferred" options on the basis of their own *understanding* (Mabelo, 2021).

It is no wonder that the Engineering Design and Development (EDD) requires a process that can transform a problem or undesirable situation into a suitable solution or a dream into reality—a problem-solving process—that is consistent with the INCOSE definition of Systems Engineering (SE):

> "An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem […] SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets users' needs." (Fossnes and Forsberg, INCOSE, 2006)

Furthermore, SE defines a Complex Adaptive System (CAS) as a "dynamic system" able to *adapt to* and *evolve with* a changing (or rather evolving) environment. "It is important to realize that there is no separation between a system and its environment in the idea that a system always *adapts to* a changing environment" (Chan, 2001)—from this definition, CASoS refers to a Complex Adaptive "System of Systems" (Sandia Laboratories, 2011).

The author suggests that the Tacoma Narrows Bridge was not designed as a Complex Adaptive System (CAS or CASoS); thus, it lacked the "resilience" to survive the adverse interactions with

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the environment (Mabelo, 2021). Most Large Infrastructure Projects fit the definition of CAS or CASoS due to their usually large scale—and for being *nested* in socio-economic contexts.

Moreover, CAS/CASoS exhibit system-attributes such as *Connectivity* (i.e., complexity arising from interrelationships/interdependencies of elements); *Distributed Control* (i.e., no single centralised control mechanism governing behaviour of the system); and *Emergent Order* (i.e., potential for emergent behaviour).

> "A project can be said to be complex if it consists of many interdependent parts, each of which can change in ways that are not totally predictable, and which can then have unpredictable impacts on other elements [as well as the environment] that are themselves capable of change." (Cleland et al, 2002)

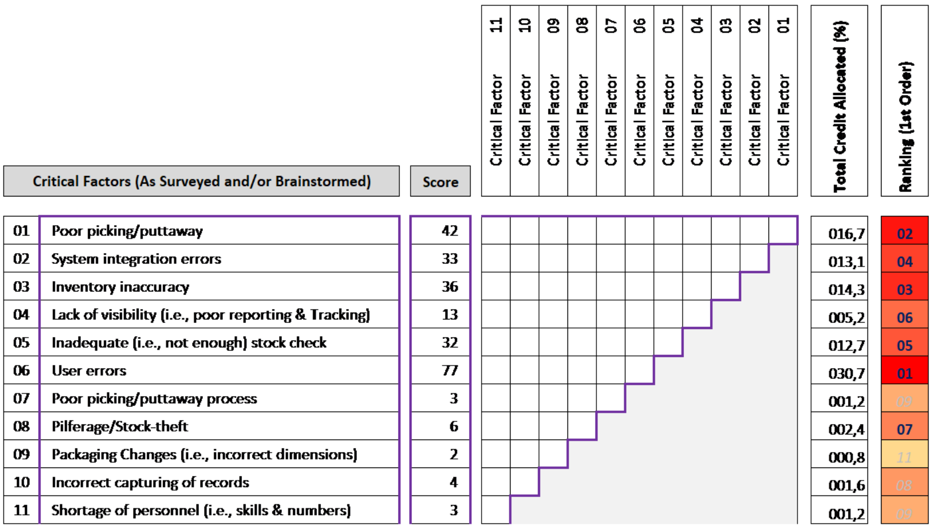
On the other hand, still on account of complexity, Sussman et al (2007, 2009) refers to "Complex, Large-scale, Interconnected, Open, Sociotechnical" as CLIOS, a *new* class of engineering systems with a wide-ranging social and environmental impact due to their "nested complexity". This occurs when a physical domain is nested within and interacts with an institutional sphere, where both entities are deemed complex. From that perspective, most LIPs are basically CLIOS—which suggests the existence of multi-dimensional problems (i.e., various problems and/or many aspects of the same problems) that must be solved and addressed about a particular *undesirable* situation.

For instance, a rapid-transit project would entail many technical, legal and socio-economic issues such as axle-loading, tunnelling, noise pollution, tariff, crime, flora protection and property rights. Similarly, a port project would not only deal with docking, cranes, bunkering and dredgers—but also with customs/security, rail connection, warehousing capacity, ecology and "weather control".

This begs the important question as to which identifiable problems (or aspects thereof) ought to be prioritised for solving by way of new design(s). The need for selection becomes more acute, even critical not only in the face of constrained resources, but more so owing to the usefulness of "*achieving more with less*"—solving the few problems that cause the most *undesirability*. The Pareto Analysis, based on the 80/20 Principle, is useful as a tool for achieving the above purpose (i.e., focus on the few items with most impact):

> "The 80/20 Principle asserts that a minority of causes, inputs or effort usually leads to a majority of the results, outputs or rewards. Taken literally, this means that, for example, 80 per cent of what you achieve in your job comes from 20 per cent of the time spent. Thus for all practical purposes, four-fifths of the effort—a dominant part of it—is largely irrelevant [Wow!]. This is contrary to what people normally expect. So the 80/20 Principle states that there is an inbuilt imbalance between causes and results, inputs and outputs, and effort and reward. A good benchmark for this imbalance is provided by the 80/20 relationship: a typical pattern will show that 80 per cent of outputs result from 20 per cent of inputs […] or that 80 per cent of results [i.e., operational improvements] come from 20 per cent of effort [i.e., projects]." (Koch, 1998)

The Pareto Analysis helps in identifying the 20 (or so) per cent of problems (or aspects thereof) which, if effectively solved, would address 80 (or so) per cent of *undesirability*; thus, this technique helps to identify or determine the root causes of defects or problems—to avert "diffusion" or wastage of effort.



	Critical Factors (As Surveyed and/or Brainstormed)	Score	Critical Factor 11	Critical Factor 10	Critical Factor 09	Critical Factor 08	Critical Factor 07	Critical Factor 06	Critical Factor 05	Critical Factor 04	Critical Factor 03	Critical Factor 02	Critical Factor 01	Total Credit Allocated (%)	Ranking (1st Order)
01	Poor picking/puttaway	42												016,7	02
02	System integration errors	33												013,1	04
03	Inventory inaccuracy	36												014,3	03
04	Lack of visibility (i.e., poor reporting & Tracking)	13												005,2	06
05	Inadequate (i.e., not enough) stock check	32												012,7	05
06	User errors	77												030,7	01
07	Poor picking/puttaway process	3												001,2	09
08	Pilferage/Stock-theft	6												002,4	07
09	Packaging Changes (i.e., incorrect dimensions)	2												000,8	11
10	Incorrect capturing of records	4												001,6	08
11	Shortage of personnel (i.e., skills & numbers)	3												001,2	09

Table 1 – Pareto Analysis Showing Ranking of "Source of Errors"

Table 1 gives an example of a modest application of the Pareto Analysis; items (6), (1), (3) and (2) make up ±75 per cent of problems in this situation. This outcome is in line with the *non-linearity* outlook of complex systems (i.e., minor action causes major impact). Any valid *output-based* attribute (e.g., frequency, cost) could be used as Score; if repeated once or twice, this analysis allows to further narrow down issues. This approach is also used to identify which classes cause different levels of consequences (in risk management) or most frequent defects/complaints (in quality management).

However, while it proves helpful for determining/identifying the root causes of any *undesirability*, the main disadvantage of the Pareto Analysis is that it does not provide solutions to issues (i.e., problems or aspects thereof), but only focuses on past data to "*distinguish the few vital from the trivial many*". A more serious criticism, nevertheless, arises from the *insidious* fact that the Pareto Analysis, in all its glory, still fails to incorporate the interactions or "connectedness" between and among the problems (and aspects thereof)—by treating them as mere isolated elements, with no bearing on each other.

In the context of the complexity so increasingly prevalent in the large and complex infrastructure sector, such can only prove a deleterious limitation, severe predicament that ought to be addressed.

Thus, the author has developed what one coins the "2nd Order" Pareto Analysis. In addition to cumulative scores, this *systemic* approach takes into account the relative connectedness (i.e., a proxy for perceived interactions) between the various elements of the problems constituting the *undesirable* situation. A Connectedness Score is worked out and used to revise the initial ranking; thus, it reflects the *relative* connectedness between every two relevant items. In so doing, the author has ensured that the CAS attributes of 'Connectivity' and 'Distributed Control' are reflected in the application of Pareto Analysis; his stance is in keeping with both Systems Thinking and Holistic Thinking.

For assuming that 50 per cent of effort will account for 50 per cent of results ('50/50 fallacy') is not the only fallacy in "engineering endeavours" (Kock, 1998); indeed, assuming that the 80/20

Principle prevails despite (or by ignoring) system-interdependencies is a *larger* fallacy—in the context of complexity.

> "The 80/20 Principle also asserts that when we know the true relationship, we are likely to be surprised at how unbalanced it is. Whatever the actual level of imbalance, it is likely to exceed our prior estimate […] Understanding the 80/20 Principle gives you great insight into what is really happening in the world around you. The overriding message […] is that our daily lives [and the EDD Process] can be greatly improved by using the 80/20 Principle." (Kock, 1998)

Thus, "*understanding*" of the 80/20 Principle is NOT gained, "*what is really happening*" is NOT known, unless and until "*true relationship*" is perceived—Due to complexity, most problems are interconnected; "*changes/remedy in one part may have effects on other parts"* of a situation (Bar-Yam, 2014).

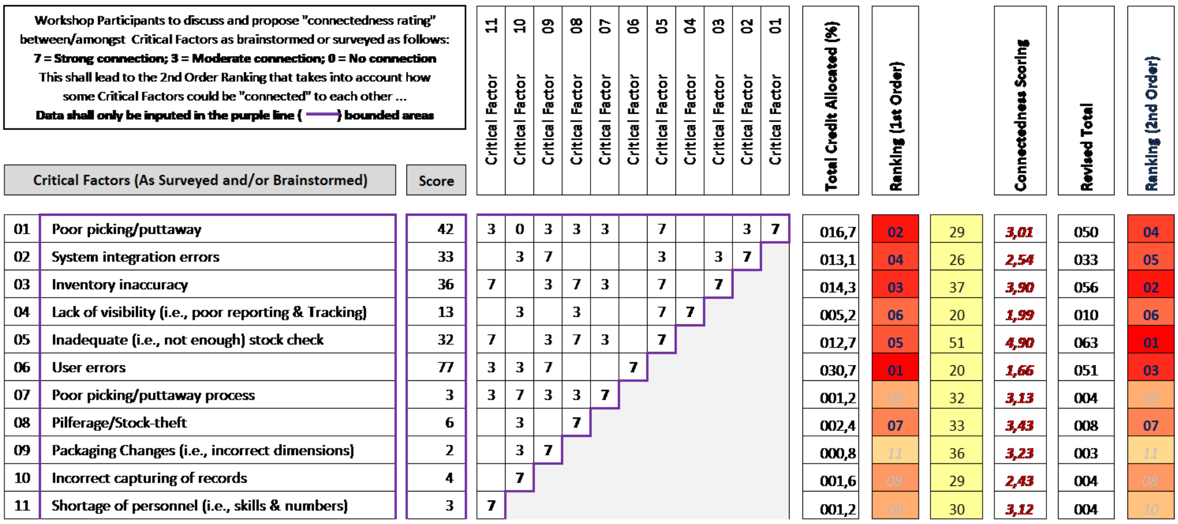
> "For [a typical] example, a development team was trying to reduce the noise and vibration for a new Lincoln Continental. They solved their problem by adding weight to the braking system, thereby creating weight and structure problems for the [interconnected] braking system team." (Bellingham, 2001)

It stands, therefore, that the Engineering Design and Development (EDD) efforts aimed at solving a particular problem (or aspects thereof) ought to consider, take into account the *systemic* reality that by solving a specific problem, the ensuing improvements are likely to "affect" (positively or otherwise) some other problems in the same undesirable situation (e.g., lack of infrastructure). One may think of the increased in water demand (i.e., new issue) in a certain community as a result of building a coal-fired power plant (which will need massive volumes of water for cooling). Donella Meadows, the "queen" of Systems Thinking, has described such Systems Architypes as:

> "Fixes-that-fail"—i.e., investment towards solving a perceived/symptoms of a problem in a particular entity, but since the underlying causes were not understood, the effort might unintendedly lead to more problems in another entity, even creating some dependence on the fix/cure thus developed. (Meadows et al, 1972; Meadows et al, 2009)
>
> "Shifting-of-the-burden"—i.e., performance improvement in a particular entity might cause the deterioration of performance in two or more other entities in the same system, but not necessarily in proximity of time and location. (Meadows et al, 1972; Meadows et al, 2009)

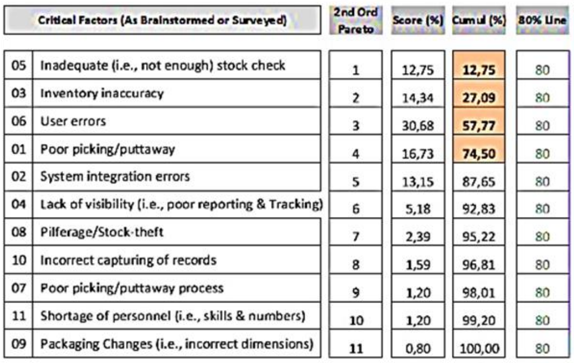
Table 2 (2a, 2b) below illustrates how the 2nd Order Pareto could be applied, based on the same 'Warehouse Upgrade Project' (see Table 1)—the most remarkable, as well as *insightful* observation is that the ranking of items actually changes once the dimension of "connectedness" is duly introduced. Before "connectedness" was considered, items (6) 'User errors', (1) 'Poor Picking/Puttaway' seemed to top the ranking list; item (5) did not even make the cut. However, by including "connectedness", the actual (viz, no fallacy) ranking turned to item (5) 'Inadequate Stock Check' leading, trailed by item (3) 'Inventory Inaccuracy'. Hence, beyond the 'traditional' Pareto Analysis, connections between items afford more *systemic* insights to priority setting.

In this instance, the connection levels (0, 3 or 7 scores) were workshopped with operations teams and summarised by the systems engineer as reflected in the spreadsheet of Table 2 (e.g., (1) 'Poor Picking/Puttaway' is *strongly* connected to (5) 'Inadequate Stock Check' and only *moderately* to (7) 'Poor Picking/Puttaway Process'—but *not at all* to (4) 'Lack of Visibility', etc.).



Workshop Participants to discuss and propose "connectedness rating" between/amongst Critical Factors as brainstormed or surveyed as follows:
7 = Strong connection; 3 = Moderate connection; 0 = No connection
This shall lead to the 2nd Order Ranking that takes into account how some Critical Factors could be "connected" to each other ...
Data shall only be inputed in the purple line (——) bounded areas

	Critical Factors (As Surveyed and/or Brainstormed)	Score	Critical Factor 11	Critical Factor 10	Critical Factor 09	Critical Factor 08	Critical Factor 07	Critical Factor 06	Critical Factor 05	Critical Factor 04	Critical Factor 03	Critical Factor 02	Critical Factor 01	Total Credit Allocated (%)	Ranking (1st Order)		Connectedness Scoring	Revised Total	Ranking (2nd Order)
01	Poor picking/puttaway	42	3	0	3	3	3		7			3	7	016,7	02	29	3,01	050	04
02	System integration errors	33		3	7				3		3	7		013,1	04	26	2,54	033	05
03	Inventory inaccuracy	36	7		3	7	3		7		7			014,3	03	37	3,90	056	02
04	Lack of visibility (i.e., poor reporting & Tracking)	13		3		3			7	7				005,2	06	20	1,99	010	06
05	Inadequate (i.e., not enough) stock check	32	7		3	7	3		7					012,7	05	51	4,90	063	01
06	User errors	77	3	3	7			7						030,7	01	20	1,66	051	03
07	Poor picking/puttaway process	3	3	7	3	3	7							001,2	09	32	3,13	004	09
08	Pilferage/Stock-theft	6		3		7								002,4	07	33	3,43	008	07
09	Packaging Changes (i.e., incorrect dimensions)	2		3	7									000,8	11	36	3,23	003	11
10	Incorrect capturing of records	4		7										001,6	08	29	2,43	004	08
11	Shortage of personnel (i.e., skills & numbers)	3	7											001,2	09	30	3,12	004	10



	Critical Factors (As Brainstormed or Surveyed)	2nd Ord Pareto	Score (%)	Cumul (%)	80% Line
05	Inadequate (i.e., not enough) stock check	1	12,75	12,75	80
03	Inventory inaccuracy	2	14,34	27,09	80
06	User errors	3	30,68	57,77	80
01	Poor picking/puttaway	4	16,73	74,50	80
02	System integration errors	5	13,15	87,65	80
04	Lack of visibility (i.e., poor reporting & Tracking)	6	5,18	92,83	80
08	Pilferage/Stock-theft	7	2,39	95,22	80
10	Incorrect capturing of records	8	1,59	96,81	80
07	Poor picking/puttaway process	9	1,20	98,01	80
11	Shortage of personnel (i.e., skills & numbers)	10	1,20	99,20	80
09	Packaging Changes (i.e., incorrect dimensions)	11	0,80	100,00	80

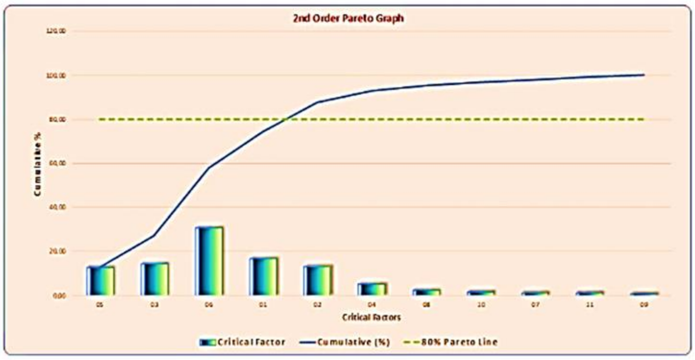


Table 2 (2a, 2b) – Analysis of "Source of Errors", Comparing Pareto vs 2^{nd} Order Pareto Rankings

Annexure

Advanced readers would be left inquisitive as to how Connectedness Scores are worked out—what "algorithms" or formulas should be used to that end; the following sections seeks to provide a "synopsis" of the calculation steps.

Assuming a scenario with three problem-items presumed to be somewhat connected. Table 3 below indicates the respective Connectedness Levels (i.e., 0, 3 or 7 scores) as F_{ij}:

Connectedness Matrix	Critical Factor 3	Critical Factor 2	Critical Factor 1	Σ
Critical Factor 1	F_{13}	F_{12}	F_{11}	$\mathbf{S_1}$
Critical Factor 2	F_{23}	F_{22}	F_{21}	$\mathbf{S_2}$
Critical Factor 3	F_{33}	F_{32}	F_{31}	$\mathbf{S_3}$
Σ	$\mathbf{T_3}$	$\mathbf{T_2}$	$\mathbf{T_1}$	

Table 3 – Connectedness Input Matrix for a 3-Factor Scenario

The idea is to work out the *weighted-average* score ρ for each Critical Factor. Considering that each Critical Factor (i.e., problem and/or aspect thereof) is interconnected to every other one, the following $\boldsymbol{\rho_j}$ formulas could be used:

$$\boldsymbol{\rho_1} = \frac{\boldsymbol{F_{11}*((F_{11}+F_{12}+F_{13})+(F_{11}+F_{21}+F_{31}))+F_{21}*((F_{21}+F_{22}+F_{23})+(F_{12}+F_{22}+F_{32}))+F_{31}*((F_{31}+F_{32}+F_{33})+(F_{13}+F_{23}+F_{33}))}}{\boldsymbol{((F_{11}+F_{12}+F_{13})+(F_{11}+F_{21}+F_{31}))+((F_{21}+F_{22}+F_{23})+(F_{12}+F_{22}+F_{32}))+((F_{31}+F_{32}+F_{33})+(F_{13}+F_{23}+F_{33}))}}$$

Now $S_1=F_{11}+F_{12}+F_{13}+\ldots+F_{1k}$; $S_2=F_{21}+F_{22}+F_{23}+\ldots+F_{2k}$; $S_3=F_{31}+F_{32}+F_{33}+\ldots+F_{3k}$ and likewise for T_j. Furthermore, $S=S_1+S_2+S_3+...+S_k$ and $T=T_1+T_2+T_3+...+T_k$. Using these abridged terms, the three Connectedness Scores are as follows:

$$\rho_1 = \frac{F_{11} * (S_1 + T_1) + F_{21} * (S_2 + T_2) + F_{31} * (S_3 + T_3)}{(S + T)}$$

$$\rho_2 = \frac{F_{12} * (S_1 + T_1) + F_{22} * (S_2 + T_2) + F_{32} * (S_3 + T_3)}{(S + T)}$$

$$\rho_3 = \frac{F_{13} * (S_1 + T_1) + F_{23} * (S_2 + T_2) + F_{33} * (S_3 + T_3)}{(S + T)}$$

The computed scores only indicate *relative* values, for comparison or ranking. In any scenario with 'k' Critical Factors, the *generic* formula is as follows:

$$\boldsymbol{\rho_j} = \frac{\boldsymbol{F_{1j}*(S_1+T_1)+F_{2j}*(S_2+T_2)+\cdots+F_{kj}*(S_k+T_k)}}{\boldsymbol{(S+T)}} \quad \text{(based on a 'k' by 'k' input-matrix)}$$

From here, embedding the above formulas into spreadsheets becomes easy, particularly when the factors are *symmetrically* coupled, as it is often the case. For example, when $F_{21}=F_{12}$, $F_{31}=F_{13}$, and $F_{32}=F_{23}$ (see Table 2a)—in which case the spreadsheet will only deal with one-half of the Connectedness Matrix.

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Additional Readings

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Pascal Bohulu Mabelo, MBA, MSc (Industrial), BSc (Civil), Pr Eng, Pr CPM, Pr PMSA, PMP, has more than 25 years of professional experience and possesses a wide range of technical and managerial skills pertaining to large and complex infrastructure projects. He has worked in large infrastructure projects as a design engineer, project/programme manager, project consultant and project management executive; Pascal was honoured to serve as national chairman of Project Management South Africa (PMSA), the leading Project Management professional association in Southern Africa.

Pascal has published books: "*Managing Engineering Processes in Large Infrastructure Projects*" (2021); he has also published "*How to Manage Project Stakeholders – Effective Strategies for Large Infrastructure Projects*" (2020) and "*Operational Readiness – How to Achieve Successful System Deployment*" (2020). He currently promotes the application of Systems Thinking and/or Systems Engineering principles and concept to unravel complexity in Large Infrastructure Projects (LIPs) in order to address their persistent risks of failure and their massive, even pernicious, cost and schedule overruns.