Complexity in Manufacturing:  
Some Lessons to Learn in Planning and Implementation  
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This paper by Sunderraman explains the need to complement the reductionism of planning' with the holism of 'learning' from the perspective of the new science of complexity. The interconnectedness, non-linearity, discontinuity, feed back loops and human interventions make manufacturing a complex adaptive system. Inherent complexity and random perturbations cause unpredictable fluctuations in manufacturing at all levels. The learning heuristics of adaptive system can effectively tackle situations in manufacturing where the underlying cause structure is unknowable or difficult to isolate. The basic understanding of the tenets of chaos and complexity helps respond to manufacturing reality. The appreciation of real-time learning as a useful complement to planning will bridge the growing divide between implementors and planners in manufacturing.

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The central conundrum of management in general and manufacturing in particular is uncertainty. Invariably, some variant of planning tools is used to bring in a degree of predictability. The students of management are armed with mathematical and statistical techniques to tackle the problems of optimization under uncertain conditions. Many of these tools are powerful approaches. However, these models and planned education rarely produce the 'successful' manufacturing professional. The successful operations executive has been a great implementor, not a meticulous planner. He views the solutions that the academics produce with skepticism, while the problems that he faces are not stimulating for academics. The 'educated' professionals attribute the less than optimal implementation results to attitude and organizational resistance to change. Practitioners grudge the reluctance of theoreticians to appreciate the reality of manufacturing. This is at the root of the divide between planners and implementors.

The Manufacturing Reality

A typical day in the life of the manufacturing personnel begins with the leftover problems of the previous day — shortfalls, shortages, last minute changes, and their adverse impact on the plan. The day also brings in new disturbances — critical machine failure, tool breakage, unsettled changeover, staff absenteeism, accident, power fluctuation, critical material rejection, dispatch shortfall, and so on.

Most of the organizations do have plans — plans for production, preventive maintenance, quality, manpower deployment, material procurement, inventory optimization and so on. Yet, the disturbing situation in manufacturing is typical of Indian industry. The scale differs, the magnitude fluctuates, the impact varies, but the central issues and the essential pattern remain the same. The detailed plan numbers get missed to varying extent. And still, surprisingly, for each cluster of micro numbers missed, some crucial macro number is almost always achieved — somehow in time.

The experienced implementor masters the complexity thrown at him at random in rapid succession. The novice in the manufacturing field soon
learns the ‘art’ of this management challenge — hardly ever in the classroom, almost always through apprenticeship with the experienced. On the other hand, the ‘manufactured’ professional of the classroom, with a basket of tools, soon finds the stone wall of resistance or gets stonewashed in the rapids of reality. If he has the stamina to stay, over a period of time, he also learns the ‘art’ of manufacturing management. Otherwise, he switches to staff function. And the divide widens. There is also a third category. A few sit on the divide, unwilling to reject the scientific methods and yet not giving up the hope of finding a method in the madness (chaos)!

If ‘chaos’ is the reality of manufacturing, the solution can also emerge from a deeper understanding of ‘chaos.’ In the last two decades, a lot of work has been done in the new science of chaos and complexity. The concepts of chaos and complexity encompass the widest range of fields — from weather to biology to economics to mathematics to ecology... The issues in manufacturing, and the essence of the erratic patterns fit some of the descriptions observed in various other fields.

This paper attempts to understand the essential patterns and underlying issues in the manufacturing sector from the perspective of the science of chaos and complexity. The ‘art’ of manufacturing reveals some scientific insights, when viewed from the new paradigm of chaos. We first begin by understanding the planning paradigm and some of its fundamental limitations.

The Essence of Planning Paradigm

The essence of scientific management or the planning paradigm is ‘reductionism’ — “Break the process into subprocesses, elements, and components, each with detailed parameters. Set standards for each, and ensure that these are inspected, reviewed or monitored to be within the limits.” The standards evolve from a combination of past experience and future expectation.

The overall output and objectives are also broken into parts and assigned to specific unit, sub-units, and eventually to individuals. Control of each of the lower order parts or elements within the set limits is sought to ensure the higher order predictability. The logic is universally applied in all domains. The financial planning manifests in account heads, budgets, and variance analysis. Even in the long-term, high uncertainty strategic horizon, planning logic prevails.

Statistical methods in process control, forecasting, and prediction based on small samples and such techniques do provide methods to handle variation. Unfortunately, in practice, the logic does not apply as effortlessly. Problems do crop up, even if all the essential standards and objectives — set after providing for a certain extrinsic variation — are actually met. Statistically, such problem events are rare and the planned consequences insignificant. Practically, the problems occur more often and with more severe consequences than predicted by statistics.

Coping with such problems regularly leads to skepticism for planning and scientific management. The implementor ‘par excellence’ learns the tricks of the trade to manage such variations. He adjusts almost the same parameters, but in a different combination and gets the throughput. He does not know or predict the precise combinations of levels for a solution, but he has an inexplicable algorithm or more correctly the heuristic for adjustments. The success of these manoeuvres eventually hits the critical macro numbers of volume, profits or mix.

Why Doesn't the Planning Paradigm Work?

There are some basic assumptions made for useful simplification in planning paradigm. The first one is about independence. The analysis assumes that one can ‘understand’ parts independent of the whole. The smaller the part and the smaller the time interval for study, the more reasonable the assumption of independence. However, in reality, the break up does not result in independent parts. The parts still remain ‘parts’ of the whole. Thus, the breaking into details cannot capture all the essence of the whole. Therefore, back in the reality domain, when the received wisdom of the model is applied, the parts behave as more than parts. The inter-relatedness adds to factors not addressed.

Even if the number of factors does not increase, the combinations of factors and their ‘variation’ over time themselves become equivalent new factors. The statistical methods of design of experiment or analysis of variance do consider these joint effects as the second order interaction effects. These solutions are more elegant but not as common in use.

The second assumption of linearity also fails in reality. Thus, inter-related, non-linear factors create variations that are not predictable as per linear statistical methods. Often, in reality, a factor is discontinuous or has some clear breaks. The effect of non-linearity and discontinuity is an order of magnitude more under dynamic conditions. Methods of integer programming and dynamic programming address a few very special cases of these situations.

And, finally, the parameters are often adjusted in anticipation of achieving some results. The future
levels of result and objectives get rolled into the present setting of the parameters. This is the crux of the planning paradigm as it rolls the future backward into the present. The conscious choice in anticipation or explicit decision of a responsive human invariably forms part of the feed forward loop.

The interconnectedness, the feed back loops, the non-linearity, the discontinuity, and the feed forward loops make the real life systems complex. It is out of these sources of complexity that the chaotic behaviour of the real manufacturing system germinates. The manufacturing reality is best characterized by what approximates a complex adaptive system.

**Complexity and Chaos: The Essence of Complex Adaptive Systems**

The key concepts of complexity and chaos are described briefly. The science is still not sufficiently developed to have a well-structured body of knowledge that can form a sequence of chapters of a textbook. However, the key tenets are clearly emerging and are powerful enough to understand applications in manufacturing even without the traditional academic rigour.

- **Complexity of the system stems more from the nonlinear, discontinuous, and adaptive interconnectedness than the mere size:** Complexity is not the result of large numbers. A few simple components with nonlinear, discontinuous or adaptive responses, when interconnected, can generate extremely complex and unpredictable behaviour. The sum of the simplicity can be complexity.
- **Complex systems are dynamic — time dependent and time phased variations are central:** A non-changing or time invariant system, however big and interconnected, never gets complex. But, even if one parameter gets time dependent, the mind-boggling complexity unfolds.
- **Complex systems exhibit self-referral, recursion or closed loops:** A typical feed back or feed forward loop could make the system complex through self-referral. There is a fractal nature to their origin. The function is not ‘\( y = f(x) \).’ It is characterized more by ‘\( y = f(x, y) \).’ This builds a self-referral or recursive iterations in solutions.
- **Complex systems have multiple ‘attractors’:** Complex systems tend to settle down to one of the many quasi-stable preferred states, known as ‘attractors.’ In the absence of any external stimulus, the system remains attracted to this state.
- **Complex systems are sensitively dependent on initial conditions and perturbations:** A small change in the initial conditions or fluctuations, after certain time periods, results in dramatic amplification, wide variations, and totally unpredictable shifts of system state to new ‘attractors.’

- **Complex systems often exhibit an arrow of time — they have irreversible components:** Irreversible change is also often intrinsic to complexity. One can go from cause to effect — one state to another state. But, the reverse is not necessarily true. Given a state, one cannot reverse the arrow of time to return to the same state from which the system previously evolved. The cause to effect of the past need not necessarily translate into effect to cause in the time reversal called future planning.

- **Complex systems bring forth order out of chaos in far from equilibrium conditions:** While small disturbances generally return systems to stability, systems at far from equilibrium conditions generate higher order configuration out of chaos. The order emerges strangely out of chaos.

There are other interesting inter-related concepts of complexity like bifurcation, state transition, symmetry of scales, and many more. The purpose of the paper is not to provide a treatise on chaos and complexity. It is to see how these concepts powerfully explain the manufacturing reality and how these can complement the planning paradigm. We will take some examples from the manufacturing context to understand the implications of the above tenets.

**Injection Moulding: A Typical Unit Level Complex Adaptive System**

Injection moulding machines are used to make plastic articles. In simple language, the raw plastic granules are heated in a barrel to flowing consistency and then injected under pressure in the closed cavity of the shape of the object. The cavity is designed to split open after the material cools to take the moulded item out.

Viewed from the planning paradigm, the injection-moulding machine is very simple. Break the process into components — material, process, and supporting machine parameters. Next, set standards! Given the material type, the object to be moulded, and the tool

- the zone temperatures in the barrel, mould temperatures, the pressures and the cycle times of various steps of the moulding process can be established for a component. The third element is the control of these parameters within the set limits. Even in simple machines, the parameters are held under control with some simple electronics. With increasing sophistication, the machine manufacturer builds a fairly comprehensive computer control.
Apart from the machines, the process also involves the tool designer, the setter, and the operators, who as an implicit or explicit team establish documented process control plans that set the limits for parameters to ensure greatest repeatability. The machine cycle times also set objectives and standards for output and productivity. And, finally, levers of adjustments are provided to the operators to reset the machine back to control, in case it goes out of control both in terms of quality or quantity of output. The machine, its intrinsic control system, the extrinsic control system of quality and quantity, and, finally, the human interface combine to form a small but complex adaptive system.

In spite of best intentions and acquired experience, the same setting does not always give the same results in a repeatable sense. The decimal differences in the 'actual' and the 'set' temperatures, minor drifts or adjustments get transmitted through elaborate control loops. These amplify fluctuations to create more than the programmed heating or pressure. This results in defects, at times dramatic, with apparently no assignable causes or any pattern. The system exhibits the sensitivity to initial condition and path.

A re-setting of some of the parameters, even out of the limits, often restores the machine to acceptable stability. In course of time or in the next set-up, the revised setting again generates defects. Fortunately, with a bit of 'kick' adjustment, the system restores to stability. Normal statistical distribution does not explain the sudden destabilization and restorations in such narrow zones of working. It is the complex interplay of interdependent loops with differences in the initial conditions that dramatically amplifies disturbances after certain cycles.

**Inventory Management and Production Control**

The commonly observed production control systems also exhibit striking similarity to complex adaptive system. The system has feed back loops, the feed forward loop encompassing forecasting and anticipation, non-linearity in productivity, discontinuity in capacities, human interventions, and built-in automatic reflex responses like batch release on reaching reorder levels.

Within limits of variation, the system behaves like the one planned using linear statistical model's. But the differences in the actual stock or off-take create classic minor shifts in the initial condition. After a number of periods, the system encounters some excess or shortages and the human interventions to correct these begin to cascade. Sometimes, these result in violent fluctuations or chaotic breakdowns — the kind we described earlier.

On analysis, the pattern defies statistical predictions. The chaos repeats later even if corrections and counter-measures are taken. It is too simplistic to attribute the deviation from plan on human errors or environmental factors. In reality, a seemingly stable system turns unpredictable due to inherent complexity. The unpredictability is due to a complex interplay of perturbations — environment or self-driven by human control decisions.

**Complexity in the Larger Manufacturing System**

Manufacturing is inundated with many perplexing examples of chaotic behaviour. The violent fluctuations are visible in wide ranging industries and economies. The helplessness of unpredictability multiplies as the issues scale up to larger systems like economy, currencies, and global stock markets of which manufacturing is but a small part.

Being man-made and having parts that are themselves adaptive systems, the dynamics of manufacturing exhibits all the characteristics of a 'rich' complex adaptive system. How do we apply this understanding in practice? What is the antidote foii complexity?

**Complex Adapative System and Learning: A Paradigm Shift**

The 'planning based on reductionism' needs th understanding of the cause structure a priori. The 'holistic learning' does not need a priori cause structure A child can cycle without understanding the dynamics of rotating bodies. A child does not have to understand the conservation of angular momentum to lean cycling. A higher order 'learning mechanism' picks uj the balancing act. In a complex adaptive system, the understanding of cause structure is intricately wovci into the learning heuristics. Separating both an< advocating one in preference to the other for planne< predictability creates an artificial divide. This is th divide that separates the practitioners and the 'educatec planners. The paradigm of 'learning without necessaril' understanding the cause structure' complements th rugged 'reductionism.'

The science of chaos and complexity explain some of the peculiar behaviour of manufacturing a a complex adaptive system. It helps integrate the caus structure based predictive planning and the heuristi driven adaptations. It explains the scientific basis c
the ‘reality’ and method behind the madness of the practitioners.

**Some Lessons to Learn from the Science of Chaos and Complexity**

- **Accept complexity — do not simplify for mathematical elegance:** First and foremost, accept the manufacturing reality. Chaos in a complex adaptive system is as natural as the predictability of the planned systems. Mathematical simplification of the reality through linearity and continuity assumptions would at times provide unrealistic solutions.

- **Limits of planning paradigm:** "One cannot solve a problem through the same level of thinking that created it in the first place" (this thought is attributed to Einstein). The human intervention as corrections in anticipation is often the very root cause of chaotic behaviour.

  Planning cannot solve problems created by the very process of planning. Learning is an option! Lower order elements of complex systems could be best left to self-adaptation within a band than be programmed and then driven as per program to the last decimal for predictable results.

- **Accept that all causes are not knowable:** It is futile to work towards identifying all the causes. In other words, the cause is not outside. It is the complexity within. Statistical correlation can always be worked out even when no cause effect relation really exists. Such mathematical relationships, in planning mode, create more disturbances.

- **Learning transcends the barrier of unknowable causes:** It is not necessary to know the cause structure for learning heuristics. Know-how is more important than know-why in practice.

- **Carry the umbrella, when you cannot predict the weather:** Redundancies and certain creative sub-optimization are better insurance against the possible chaotic behaviour of the complex systems. The more optimal the solution, the lesser the room for manoeuvre. Instead, the creative sub-optimization gives better robustness. The overall success of a bundle of suboptimal but collectively more likely alternate solutions is better than that obtained by relying on just one ‘optimal’ solution.

- **Integrate carefully — isolated subsystems are not outright bad:** It is a fad these days to integrate everything. Parts have to be integrated with the whole! Yet, over-integration can create destabilizing feed back and feed forward links. As a corollary, isolation prevents escalating cascade of disturbances. The classic example is the electrical network — beyond a limit, the system automatically isolates to minimize cascaded tripping. It is also wiser to integrate at higher levels than across the board. In case of onset of chaotic fluctuations, the isolation is easy.

- **Build explicit time delays to prevent instability:** Fast response to anticipation can be counter-productive to stability. Small calculated stock cushions, excess capacities, deliberate delays, and measured batching do better in a rapidly changing environment.

- **Simulation is a powerful tool to master dynamic complexity:** Simulation can create in a crucible what reality takes years to unfold. The combination of multi-trial 'fast forward' provides the range of probabilities of potential outcomes. Graphical display of software like PROMODAL or elegance of CRYSTAL BALL makes simulation fun.

  Yet, the purpose of simulation is to look beyond the inanimate part of the system and the probabilities. The power of the simulation is best leveraged to create a learning platform. Human control interventions can themselves be built in as options'. The learning comes from interplay rather than an analytical understanding of the underlying cause structure.

  Flight simulator is a classic example. It is now accepted as a legitimate component of experience. The issue is not how accurately the change of wind velocities while landing is programmed. It is how well the pilot responds to such change that improves the effectiveness of simulation as a learning mechanism for complex adaptive system. In the manufacturing domain, the use of simulation is beginning to shift from predictive to learning tool.

- **Learning need not be imposed; it is the most natural behaviour:** Learning is in the very nature of the complex adaptive system. Learning for human begins even before birth and transcends death through language and literature. A system interwoven with human, therefore, naturally learns if the artificial barriers to learning are removed.

- **Retained learning is not just levels of parameters; it is the heuristics of adjustments:** Learning is not just the retained knowledge base of product break up, sequence of operations, target levels of parameters or cause effect relationships. It is more than the static knowledge. It is dynamic — the process and direction of adjustments, selective perturbation, adaptation heuristics, and judgement to differentiate the special or common and global or local causes.
This is essentially the reason why the technology transfer of drawings and processes often fails. The dynamics have to be learned locally. They can never be transferred fully in the drawings and processes. Recursive learning still remains the cornerstone of development.

The lessons from complexity are generic. They apply to most of the contexts displaying complex behaviour. The following brief illustrations provide practical experience in dealing with manufacturing complexity.

**Tackling Complexity in Practice: Some Examples**

After rigidly driving towards adherence to standards in our plants/ the standards have been 'relaxed' in processes that exhibit complex behaviour. More leeway has been given to experienced operators. The adjustments made just to adhere to standards in brazing, welding, injection moulding, and thermo-forming operations have reduced. The operators also monitor the nature and direction of adjustments. Over a period of time, the learning heuristics gets captured. While the precise repeatability of the parameters has reduced, the overall speed of learning and consistency of output has slowly improved. Also, the retained learning drives faster stabilization. Though the quality plans continue to guide the starting point, the experienced and learned operators are not constrained by the rigidity of parameters.

In the last two years, the market for consumer durable has experienced wide swings. The planning paradigm in our plant is tempered with learning paradigm for production and inventory management. The process creates plans but integrates at much higher levels. The lower order plans are left for self-adaptation. The control actions are balanced by equally powerful learning actions in cross-functional team review setting. The process known as PSI combines the hard with soft. in all, the actions have had beneficial impact on inventory turns and tremendous response flexibility to market fluctuations.

**Complexity and Chaos: Some Suggestions to Nurture Manufacturing Professionals**

The understanding of this subject is still evolving. It is still at a stage of curious exploration, exciting observations, striking discovery of similarities across widely divergent fields, and building a coherent body of knowledge. The applied chaos or complexity theory is still in its early phase. However, an appreciation of need for balance of planning and learning — hard and the soft — needs to be built. It is necessary to accept the human superiority in learning. This will break the added complexity built on the assumption of human incapability, infallibility, mistrust, and suspicion. The learning laboratories will substitute for some of the forced mathematical predictability. The more we understand manufacturing as complex adaptive systems, the more these would become simpler but powerfully adaptive. The appreciation of inherent complexity will dissolve the planner-implementor divide.

**References**