

OVERCOMING LIMITING CONTRADICTIONS IN A CONTINUOUS MANUFACTURING PROCESS

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Abstract

Engineering systems, and particularly their associated production manufacture operations, are subject to limits in their fundamental capability. Understanding how and why these limits occur is an essential precursor to overcoming them. The paper examines how TRIZ tools have been used to help gain a better understanding of system evolution, and then provide systematic means of overcoming the identified limitations.

The focus of the paper is the film coating process employed in the large-scale production of photographic printing paper. The paper plots the historical evolution of the manufacture process from the 1960s to the present day, and, explores how TRIZ has been used to identify further opportunities for step-change increases in operational output in the future.

A key element of the paper concerns the identification and elimination of limiting or 'root' contradictions within systems. Theory on emergence of limiting contradictions and how TRIZ can help engineers to define which of all the contradictions present is the key improvement bottleneck is presented. Strategies adapted from the Theory of Constraints and critical path analysis have been included in this methodology and the benefits accruable through their integration are detailed.

Introduction

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Photographic Paper Manufacture Process

The overall process involved in the manufacture of photographic paper involves three main parts; firstly coating the paper, then drying the coated paper, and then web handling – where the long lengths (circa 3.5km) of coated paper are rolled into a form which permits easy transport and downstream manipulation. Each of these three main parts is described in relation to the way they have evolved over time below :-

The Coating Process

The coating process is complex and is the culmination of a number of systems all operating to their optimum at the correct time. If these processes do not function correctly waste product will be produced at a high cost.

In the coating of photographic products often there are multiple layers of light sensitive emulsions laid down on to a moving substrate. These layers can be applied to the substrate in a number of different ways.

Air Blade Coating – here liquid is pumped through a slot and onto a moving substrate. The only control is achieved by having an air blade downstream of the coating point removing and returning excess fluid to the solution supply system. This system only allowed one layer of fluid to be coated at a time meaning either two or more coating points in a line for multi-layer coating. Also, if the web traveled too fast the coating quality became too poor. Normally seen by uneven coating in the machine direction. Should this defect be seen in the coating the machine operators would do some careful tweaking in order to try and balance the flow rate against the air pressure.

Slot coating (Figure 1) allows one layer to be laid down at a time. Liquid is metered through a pump and into the chamber behind the slot. The chamber and slot are designed so that the pressure distribution is even across the exit of the slot. The tip of the slot is kept very close to the moving web and a vacuum is applied to the lower edge of the exit to the coating slot so that the stability of the bead is maintained. The application of the coating liquid is of a much higher quality. Wet lay down is controlled by width of the coating gap and this is controlled by web tension and web stiffness. For a thinner coating very tight coating gaps are required and these can be the cause of a number of problems. They are mainly streaks in the coating or damage to the running web. Slot coaters are normally used for the application of one layer at a time. This means that the web would have to be run through the machine a second or third time becoming a costly method of coating.

However slot coaters have been designed for the application of two or more layers, but slide bead coaters are much better for multi-layer coatings.

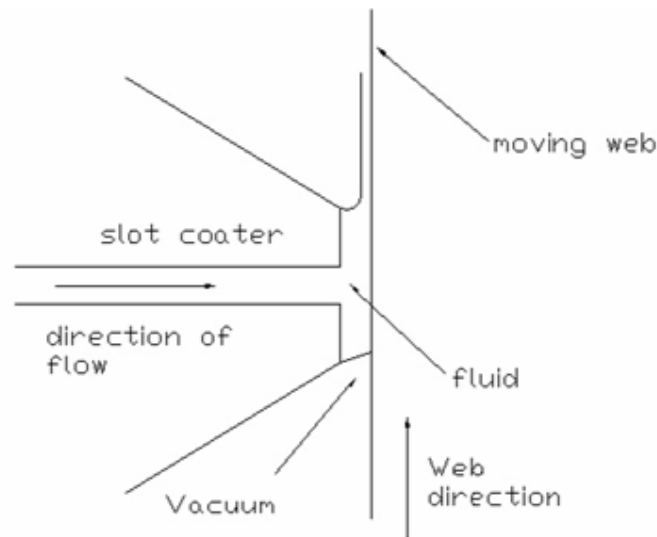


Figure 1: Schematic of Slot Coating Process

Slide Bead Coating

Slide bead coating (Figure 2) was first developed during the late 1950's and allows a number of layers to be applied at the same time but has speed restrictions. Slide bead coating is a series of slots mounted together but open to atmosphere on one side, unlike the slot coater described in the previous section. The liquid is still metered through the slot by pump but the fluid runs down the face of the slot, inclined at an angle and onto the moving substrate. Where multiple layers are required a series of slots are built together and the fluid from one slot will sit on the top of the fluid from the next slot making a package of different layers. The layers will not mix if the surface tensions and viscosities are correctly balanced. Once again the tip of the slide bead coater is very close to the web and to maintain stability of the fluid over the gap between the web and the coater a vacuum is applied to the lower edge of the fluid. It is quite possible for 6, 8 or even more layers to be coated by this method however there is a limitation the upper viscosity of the liquid to be coated. This presents the problem of the more layers to be put down the higher the water load that the drier has to contend with and hence rather than be able to maintain the coating speed it has to be reduced. So more often than not the limiting contradiction with such plant is the drier size and it will be seen later on how TRIZ can be used to overcome this contradiction. A further problem with this method is that of air entrainment. As the coating speed increases it becomes more difficult to prevent air from getting underneath the coating causing a bead failure and a severe coating defect.

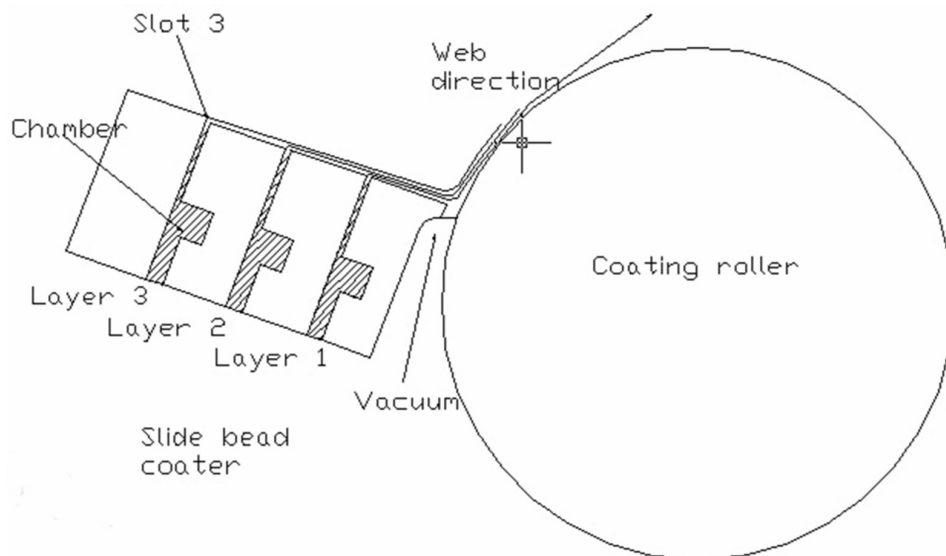


Figure 2: Schematic of Slide Bead Coating Process

Curtain Coating

The curtain coater (Figure 3) uses a similar device to deliver the fluid as a slide bead coater allowing a number of layers to be applied at the same time. Here the device is lifted above the moving substrate with the fluid forming a falling curtain. The height of the curtain means that it is impossible for particles to get trapped and cause coating defects as seen in previous examples of coating methods. By raising the liquid and forming a sheet the speed of the falling fluid can be matched with that of the substrate reducing any shearing action the fluid would see in the slide bead and slot coating methods. For successful curtain coating a minimum flow rate is required and therefore a minimum length of drier. It is possible with this method to reduce the amount of water in the liquid hence raising its viscosity. Here it is possible to raise the machine speed and use the same length of drier.

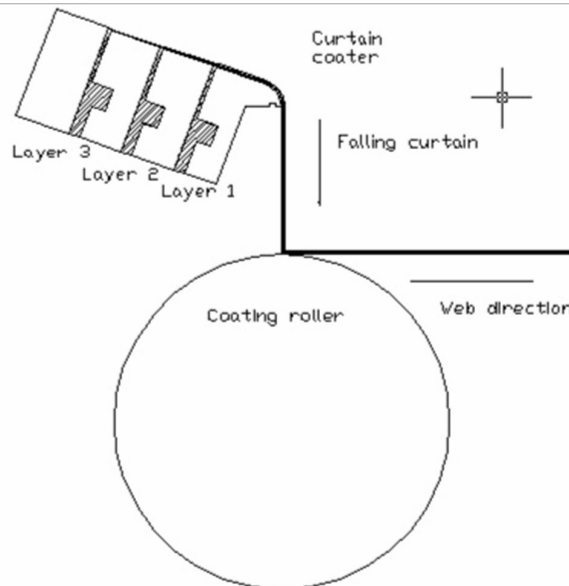


Figure 3: Schematic of Curtain Coating Process

Drying

Festoon Drying

Festoon dryers were the first design adopted by paper manufacturers with the web being hung out to dry on a slow moving track. This involved many thousands of feet of web being

suspended at any one time. It also took up a great deal of space and was very slow and was typically used with the air blade and first slot coating techniques. The disadvantage here was that the web was dried by ambient temperature air and would not dry evenly often giving the web a set.

Spider Machines

Spider dryers replaced the loops of the festoon with a tensioned web going around the outside of the coating machine for a number of revolutions until it came to the rewind end of the machine. This was much better for the drying process as the paper was kept taught during drying eliminating the possibility of the web taking a set but still the air was ambient temperature not allowing the higher coating speeds needed to be able to reduce the manufacturing costs.

Spider driers were eventually replaced with arched driers, enclosed with raised air temperatures. Driers could be shortened and machine design became simpler. Air impingement allowed much better control of the drying with temperature-controlled air being conditioned and filtered before it came into contact with the coated side of the web. The air was blown into a box through which the web was travelling over a series of rollers following an arch.

Flat Bed Drying

The advent of the flat bed dryer allowed for higher pressure air impingement directed straight at the web through either nozzles or holes. The air temperature and humidity can be controlled in a precise manner but the drier is very long and can take up a lot of space.

The next generation of air impingement took the flat bed drier and folded it into a stack of zones taking up less floor space but being tall.

Fuji have gone a step further and used the outside of a large tube as the back of the impingement drier with the web travelling along the tube in a helix.

Air Floatation

Trimming the rollers in the flat bed drier has led to the development of air floatation driers. Their function of the rollers has been replaced with the use of carefully controlled air movement. Typically the Coanda effect has been used to its best advantage.

Trends of evolution push us in the direction of using fields as going towards ideality and more controllable fields.

A simplified history of the evolution of the drying process as a function of time is illustrated in Figure 4 below. The figure speculates – consistent with the trend predictions detailed later in the paper – that a new drying paradigm involving a switch from air to fields looks set to take over at some point.

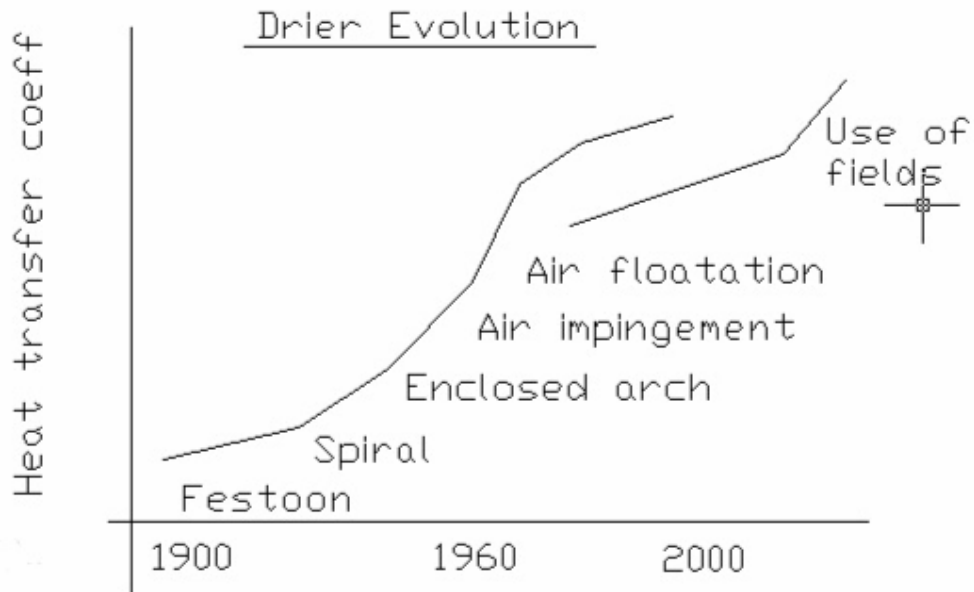


Figure 4: Simplified Evolution History of the Coating Drying Process

Web handling

The continuous process requires at least two rolls to be mounted on an unwind turret at any one time. The first will be unreeling the second will be prepared for the join to take place. At a predetermined time the join will be made so that there is no disturbance to the coating process. It was not uncommon to take 8 hours for a single 1000m roll to be coated on an air blade machine using festoon drying.

With the slot method and slide bead method of coating it is important for the join to be accurate. This is so that the join can pass through the small gap between the coating roller and the tip of the cascade. In order to achieve this process the join must be of the butt variety i.e. the ends of the web are very close together but not touching.

When machine speeds were slow it was possible for the unwind operator to make a join by hand with the aid of a small accumulator which would slowly empty until the join had been made. The operator would then start the unwind, which would run slightly faster than the coating speed, filling up the accumulator. This approach was typical when slot coating was the norm and drying was either by the festoon method or the arched impingement method.

With the development of better drying, machines could become faster but the operator could not keep up with the speed when the join was required.

Magazines were made larger but more importantly the trend of evolution was towards semi automation of the joining process and the removal of human intervention. The down side to this was increased complexity.

The curtain coating process has allowed a considerable machine speed increase and in order to allow the continuous process to run join cycle times have had to reduce. This has meant complete automation of the join sequence without human intervention at all. Machine speeds are ever increasing and it has been necessary to merge and remove mechanisms of the joiner so that magazines can remain the same size whilst speeding up the cycle time. In recent times joiners have been developed that can make a butt splice join without stopping the web hence allowing the magazine to be trimmed from the process completely.

The rewind machines have undergone similar evolutions. Twin turrets have been required to allow for the continuous process. When running at very slow speeds the operator would cut the web by hand and attach it to the new core. This would be reliable on tape on the core or the coefficient of friction between the paper and the core.

With the increase in speeds mechanisms were introduced to aid with the cutting of the web and attachment to the new core. In the first instance a magazine was used in the same way as for joining a new roll into the process. New machine design has allowed the trimming of the rewind magazine from the process.

Faster web speeds can cause the web to lift off the surface of small diameter rollers, a similar process also happens to a reeling roll. As the speed increases the air thickness boundary layer running with the web increases.

To eliminate this problem roller diameter, angle of lap or web tension can be increased. As rollers get larger they become heavier which means more motive power to move the web and in the case of free running rollers very sensitive films may be damaged because of the loss of traction between the larger roller and the sensitive film.

For reeling tension profiles become critical but after a certain point other methods of eliminating the air from the roll must be found. Typically the introduction of a lay on roller which is in contact with the building roll will help the situation. Once again with sensitive materials at high speeds the lay on roller cannot be used so the trend of evolution is toward a controllable field.

With non-photographic materials static electricity may be used but in the case of photo products air pressure at the nip point has the same effect and has been used by a number of organizations to great effect.

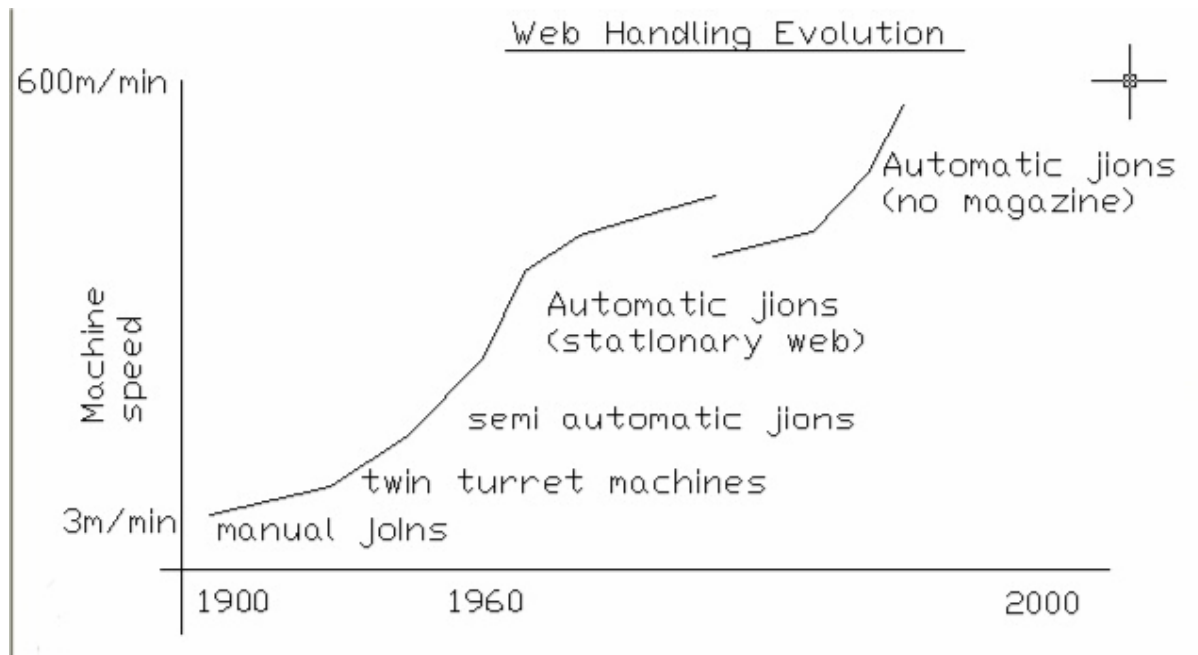


Figure 5: Simplified Evolution History of the Web Handling Process

Main Useful Function

The primary function of the combined coating, drying and handling manufacture process is to produce high quality photographic paper at minimum cost and harm. At the highest

level, the evolution of the process may be seen to have been governed by the increasing ideality trend found within TRIZ.

The described evolution of each part of the process is a story of achieving precisely such ideality (benefits/(cost+harm) increases. In the preceding descriptions of these stages, it is evident that there have been a series of step-change improvements. In this sense, the process is highly typical of other manufacture processes:-

- 1) a method of production is devised and introduced
- 2) the desire to maximise useful output at minimum cost provokes a programme of improvement (often known as 'continuous improvement' in most organisations) focusing on 'optimisation' of the assorted variables present in the system. Within each of the coating methods described above, it is possible to record a series of development activities in which things like coating thickness, gap height, web-speed, temperature, coating constituency, and a host of other possibly related parameters have been systematically (or not) been varied in order to establish the 'optimum' level of performance.
- 3) As time progresses, and the desire to continue to achieve increased output and decreased cost prevails, because the process has been 'optimised', it becomes progressively more and more difficult to obtain any further increases in performance.

This phenomenon is absolutely fundamental to understanding the governing dynamics of evolution. In simple terms; systems hit limits. These limits may be observed most effectively if the ideality of the system is plotted as a function of the time over which the system has been improved – from its conception to optimisation and maturity. Plotting this data gives the classic s-curve profile common to all systems (actually, there are details which can distort the shape of the curve; but the flattened profile at the top of the curve is always present). We can usually also obtain a similar characteristic shape if we just look at the benefits aspects of the system. In this case where the primary interest is output rate of quality paper, for example, it is possible to also see the characteristic s-curve profile (Figure 6) if we plot output against the time history of the system.

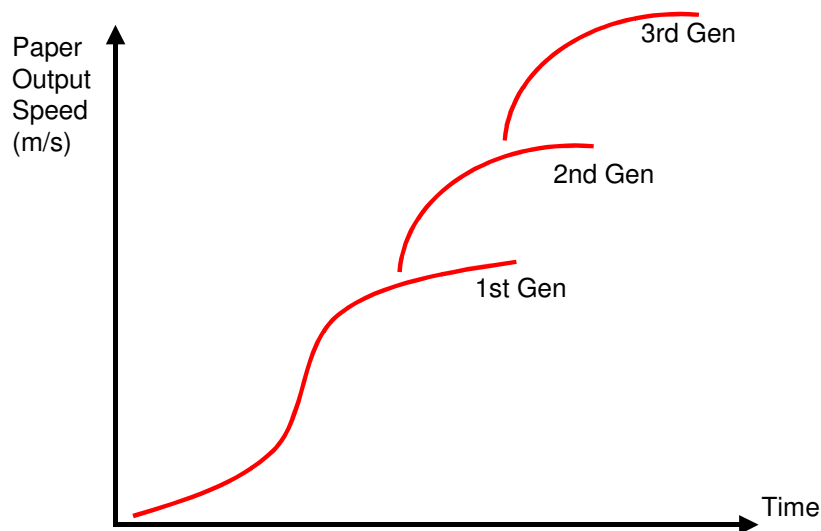


Figure 6: Systems Hit Fundamental Limits – S-Curve Characteristics

The flattened profile at the top of the curve is a fundamental characteristic. It is indicative of the fact that every system has an ultimate level of capability, beyond which no amount of optimisation will ever allow the system to pass.

This phenomenon becomes a problem once the fundamental capability of the system becomes inconsistent with the desired performance targets – Figure 7. The point about the word ‘fundamental’ is that it means precisely that. Companies often state that their improvement initiatives ‘fail’, when in actual fact they are simply failing to realise that the system they are operating has hit a limit beyond which it is incapable of passing.

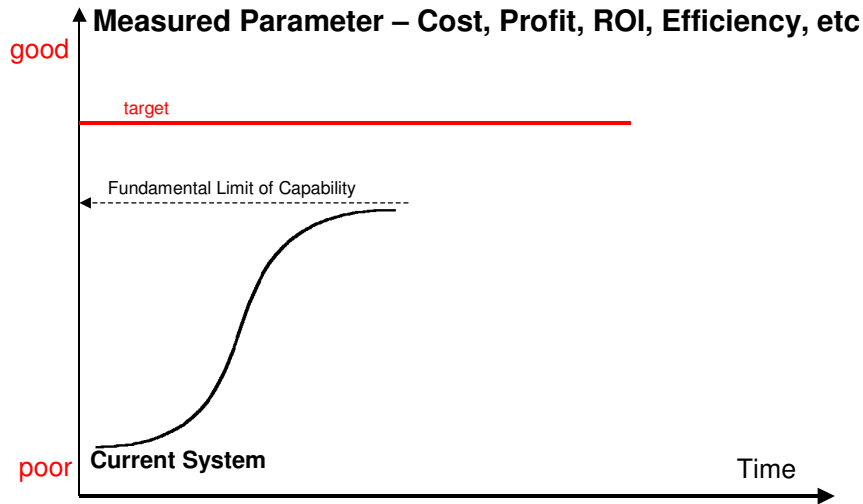


Figure 7: Commonly Experienced Inconsistency Between Target and Capability

What TRIZ research has uncovered is the fact that when this kind of inconsistency situation has arisen, the only possible courses of action involve changes to the system. Figure 8 suggests that this implies the need to discover a new s-curve. While this is true, it is an implication that requires some clarification; s-curves in the TRIZ context meaning much more than the single curve that is often perceived to define a system (e.g. ‘the s-curve for photographic paper’) in that every single component within a system contains its own family of s-curves. Consequently, while expressions like ‘finding a new s-curve’ or ‘changing the system’ perhaps imply radical changes, they may actually mean only that a component of the system needs shifting to a new design paradigm.

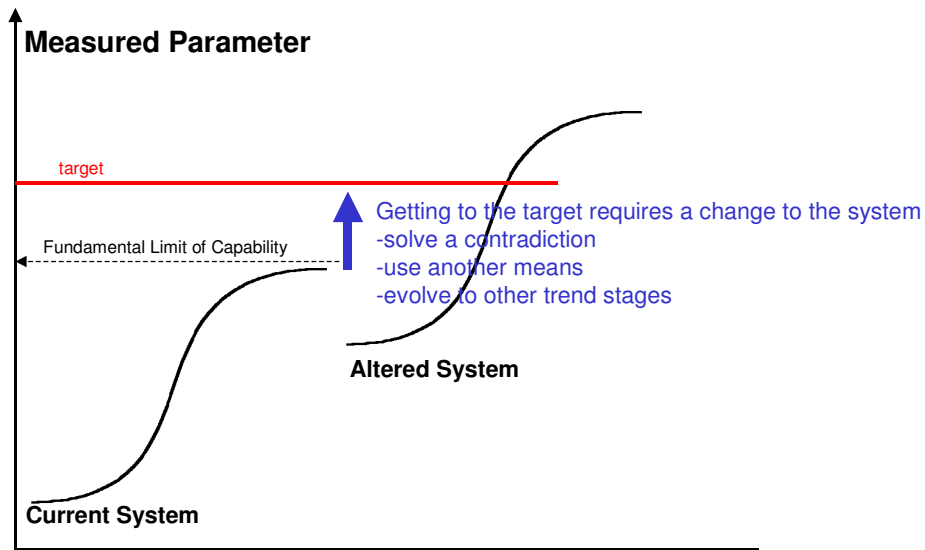


Figure 8: Principle Mechanisms of Shifting From One S-Curve to the Next

Knowing Where To Make The Jumps

When trying to improve the performance of processes like the one discussed here, it is important to establish *where* improvement efforts should be focused in order to secure the greatest benefit per unit of effort expended. The Theory of Constraints (Reference 3) offers a good method for assessing systems and what elements of those systems present bottlenecks and limitations. In many senses this bottleneck identification process is very closely linked to the concept of limiting contradictions (Reference 4).

The process of identifying bottlenecks requires the construction of a model of the production system. This model may be simple or complex depending on the type of process under evaluation. The key to successful use of the model, however, rests primarily with the identification of operations that are sequential or conducted in parallel with one another. Critical path analysis methods are usually adopted here. With regard to the photographic coating process, it is clear from the preceding descriptions that there are both sequential and parallel operations taking place, and that there are a number of interactions between operations that also serve to complicate the model. Figure 9 illustrates some of the key elements and interactions in the system.

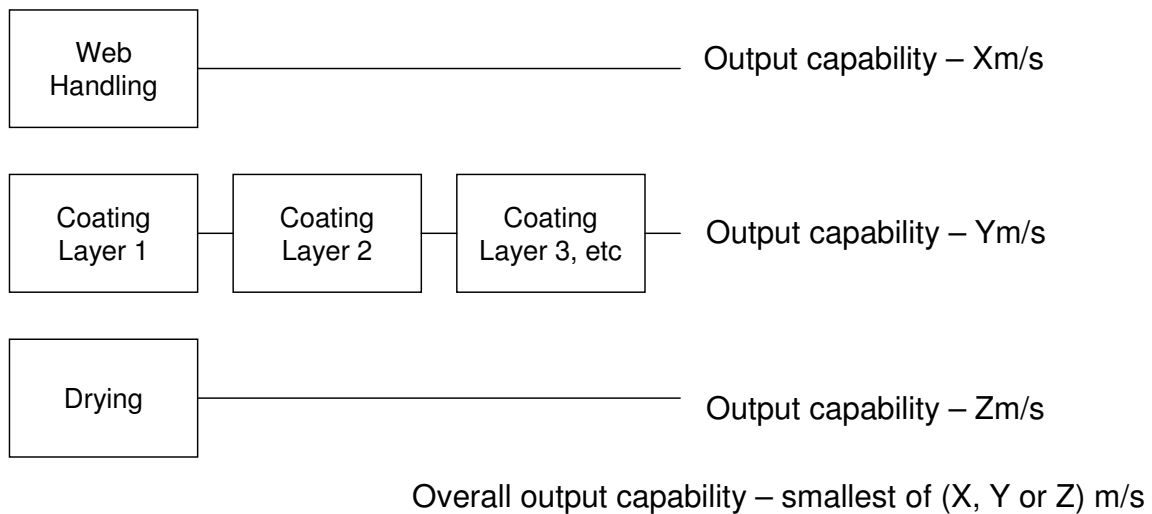


Figure 9: Simplified Model of Photographic Paper Coating Process

What the model makes clear is that the three parallel operations 'coating and drying' and the over-riding process of 'handling' essentially determine the critical path process time, where the coating process may contain a number of sequential steps. The distinction between parallel and sequential operations is that only improvements to the parallel operations on the critical time path will result in an improvement in overall process time. Thus overall production time for this process can be determined either by handling limitations *or* the coating process *or* the drying operations. In other words, there is little point improving the drying process capability if the web handling operation is the time limiter.

Of course, there are interactions to consider (handling becomes easier if the drying operation is speeded up or requires less space for example), but generally speaking, the overall capability of the photographic paper coating process will generally be determined by a flip-flopping between the three main parallel operations; so that if handling is the current limiter, an innovation that causes this operation to be significantly improved (as was the case in the jumps from single to twin turrets, or with the introduction of new tensioning mechanisms) causes coating or drying to become the limiting elements; which in turn causes these issues to become the focus of innovative efforts. It is possible to see

this shifting centre of attention most clearly in the above example where the introduction of curtain coating caused an increase in process speed that meant that the web-handling roll-change time became the new process limiter (and subsequently prompted the introduction of the fully automated changeover system). And so this process carries on... at least until such times as resolution of a new contradiction demands a re-think of the whole process.

By way of an aside this shifting focus phenomenon may be seen to be a dominant influencing factor responsible for the original TRIZ trend relating to the rate of evolution of systems happening in fits and starts.

Three Mechanisms for Jumping S-Curves

1) Contradictions

The emergence and resolution of contradictions may be observed at several points in the history of the photographic paper coating industry described earlier. Some of the more interesting ones include:-

With regard to the drying process, it is possible to see how a limit is the length of the drier. The limiting contradiction that has emerged involves the fact that to increase drying capability requires additional drying length, and the building can no longer accommodate any of the required additional length. This can be examined as a technical contradiction as follows:-

Thing we are trying to improve – SPEED

Thing that gets worse – LENGTH

TRIZ recommends – 13 Other Way Round

14 Spheroidality (increase curvature)

8 Counterweight

It is possible to see from at least the first two suggestions how just about all of the drying innovation jumps – from festoon to spider to arched to the Fuji helical motion solution, and from the flat-bed to the folded flat bed – could have been derived.

It may also be seen how the Counterweight Principle was used (in the form of balancing hydrodynamic forces) to solve a similar speed versus length contradiction in the evolution from slide bead to curtain coating methods.

The coating and drying evolution stories also contain several examples of emerging contradictions between speed and the stability of various aspects. In this regard, TRIZ recommends the use of Principles 28, Mechanics Substitution (e.g. replacement of rollers with air-jets), Homogeneity (the shift from slide-bead to curtain coating), and Segmentation (the initial shift from slot coating to slide bead). Only the other suggestion for this particular contradiction – Principle 18, vibration – has not thus far been utilized. One may surmise that the benefits likely to be attributable to introducing ultrasound (something that the Principle is pointing towards) as a means of assisting the flow and controllability of the coating viscosity have as yet to be accrued.

Since a very significant objective of the overall process is to improve its speed (or 'productivity' – also featured in the Matrix), it is in fact possible to identify how several contradictions featuring this as the improving parameter have emerged and been solved. Of course, using the Contradictions part of TRIZ is not the only means of improving systems; the Trends parts map a lot of the disruptive shifts in a perhaps more direct manner:

2) Trends of Evolution

Like the contradictions tools, the TRIZ trends also provide a generic problem to solution mapping framework. The main tasks of the problem owner are mapping their specific problem to and from this generic framework.

Several of the TRIZ trends can be mapped onto the coating process problem. Figure 10, for example, illustrates the geometric evolution trend

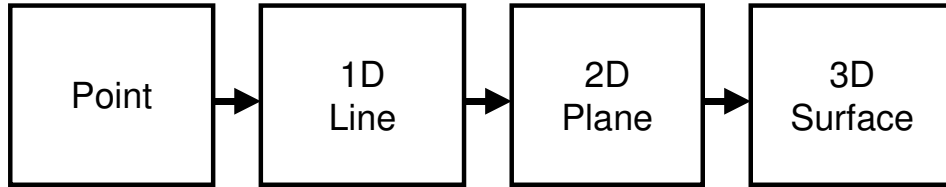


Figure 10: 'Geometric Evolution of Linear Structures' Evolution Trend
(picture from Reference 1)

The evolution of the various different drying methods can be mapped along this trend, with, for example, the shift from flat-bed to folded flat-bed representing a jump from 1D to 2D and the Fuji 'helical' system representing a further jump to, if not fully 3D, then at least 2.5D.

Similarly, the evolution of the drying system from solid rollers to current use of air jets is an example of the Dynamisation trend (Figure 11) in action.

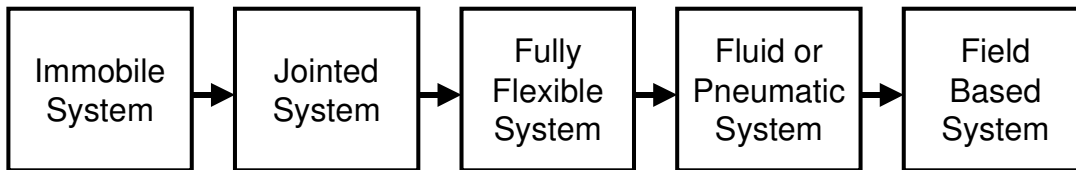


Figure 11: 'Dynamization' Evolution Trend

The 'evolutionary potential radar plot (Reference 4) has recently been introduced as a means of displaying a lot of the relevant trend information in a relatively small space. Constructing these plots for certain key parts of the coating, drying and web-handling processes – Figure 12 – reveals that, despite the apparent maturity of all three, there remains significant amounts of untapped potential.

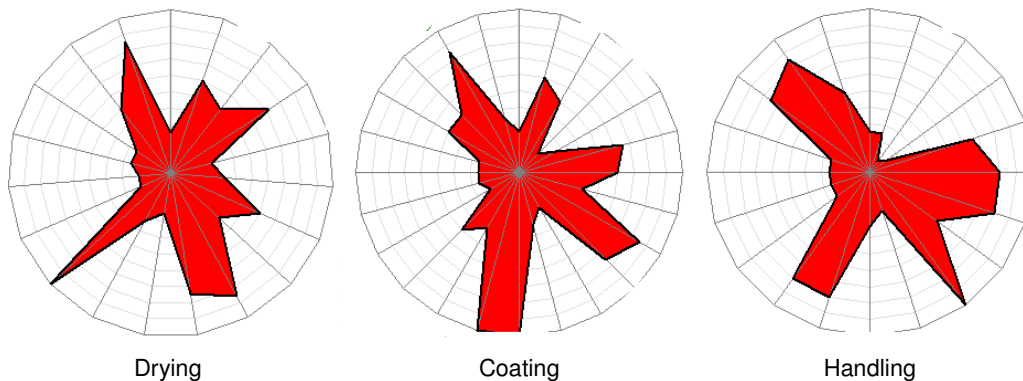


Figure 12: Summary Evolutionary Potential Plots for Coating, Drying and Handling Processes
(Note: axis labels omitted for commercial reasons)

It is possible to then use these plots as the basis for examining future direction opportunities. For example, it is clear that none of the key systems have as yet taken advantage of the benefits achievable by following the rhythm co-ordination trend illustrated in Figure 13. Use of this trend in the air-jet system may be seen to offer the potential to both improve drying performance, and reduce energy consumption. Similarly increased evolution along the geometric evolution and dynamization trends when thinking about air-jets would suggest possible incorporation of moving, swirling flows and non-parallel flows – both of which should deliver better drying performance in a shorter amount of space.

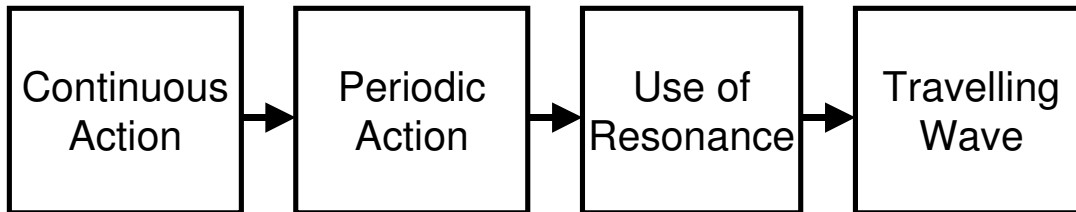


Figure 13: 'Rhythm Co-ordination' Evolution Trend

The application of the evolutionary potential concept can lead, in fact to several more possible evolution jumps in the overall photographic paper coating process. It represents only the second of three main strategies, however. The third is the use of scientific effects and the 'knowledge' parts of TRIZ.

3) Knowledge

The knowledge aspect of the TRIZ toolkit is essentially constructed on the idea of functionality, and the fact that all systems exist to deliver useful functions. In evolving systems towards their ideal final result, therefore, it is important to ensure that the most effective means of delivering a particular function are being utilised. Historically, it has not been easy to identify other means of delivering a function. Today, this is no longer the case, and several TRIZ 'databases' have been constructed such that, having abstracted a given functional requirement, it becomes possible to identify all of the known ways of delivering a particular function. With regard to the specifics of the photographic coating process, it was clear that when the paradigm shifted from primarily mechanical systems to increased use of fluid and air-based systems, that there was a need to identify the 'best' ways of utilising those elements. In TRIZ terms, the abstracted function was 'move liquid' or 'move air'. Databases like those found in Reference 1, for example, would then very quickly lead to a list like that illustrated in Figure 14.

The list clearly identifies the Coanda Effect and its ability to help solve the 'move air' problem – a solution that the industry has adopted to a substantial degree. The list, of course, also points to a number of other means that may add further benefit – the Cholosky Effect for example may turn out to be very beneficial in controlling boundary-layer flows at various points in the system.

The power of some of these knowledge databases, however, raises a certain danger, in that they suggest that 'finding another way of delivering the function' is the be all and end all of innovation, when in fact the actuality is that to work effectively, it must work in conjunction with the other TRIZ tools. This is particularly apparent if we find ourselves concentrating on the above 'move air' knowledge when everyone else has shifted along the dynamization trend to the 'fields' evolution stage.

Acoustic Vibrations
Archimedes' Principle
Bernoulli's Theorem
Cholovsky Effect
Coanda Effect
Diffusion
Ejector
Electrocapillary Effect

Electro-Osmosis
Electrophoresis
Electrostatic Induction
Fan/Compressor
Ferromagnetism
Gravity
Inertia
Jet Flow

Pascal Law
Ranque-Hilch Effect
Shock Wave
Spiral
Thermal Expansion
Peristaltic Pump
Vacuum
Venturi Effect

Figure 14: Some Ways of Delivering the Function 'Move Air'

Conclusions

- 1) Systems are subject to fundamental limits in their evolutionary potential within a given design paradigm. Once this limit has been reached, new paradigms have to emerge if further benefits are to be achieved. The TRIZ trends, contradictions and knowledge tools provide systematic means of overcoming limiting contradictions.
- 2) A photographic paper coating manufacture process has been examined. Historical evolution of the system fits the limiting contradiction model. TRIZ has been used to identify strategies that may be adopted in order to provide further improvement of the system.
- 3) The Theory of Constraints and the idea of critical path analysis also have much to say about how systems evolve, and how we should best focus our inevitably limited resources to achieve the greatest possible benefit per man-hour invested.

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