

Compressor System Technology: Evolutionary Potential and Evolutionary Limits

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ABSTRACT

For the last 5 years, the world has generated an average of 550 new patents per year in relation to the design of compressors. The paper describes a programme of systematic analysis of these and earlier patents. The purpose of the research has been to establish the evolutionary status of compressor system technology across a number of the different sectors of the industry, to benchmark the capabilities of the different sectors relative to one another, to benchmark capabilities relative to a *global* measure of evolutionary maturity and then, most importantly, to identify future development directions and opportunities for the industry.

INTRODUCTION

This paper is aimed at setting a global context for compressor technology. Such a broad-ranging ambition requires the foundation provided by the single largest study of innovation ever conducted. That study started in the former Soviet Union in 1946 (Reference 1), and has now accumulated data from close to 3 million successful solutions in a range covering all areas of human endeavour. One of the main findings from that research has been that different scientific and engineering disciplines spend a large proportion of their time re-inventing what has already been discovered in other areas.

A large part of the focus of the more recent (1998-2004) research has been on the mechanics of system evolution (Reference 2). The research has had a particular focus on

what happens when systems evolve in a non-linear, discontinuous manner from one way of doing things to another. A large part of the interest here has been on the identification of jumps that are common to all industries and disciplines. To date, the research has uncovered 35 such generically applicable discontinuous technology evolution trends. Although it is something of an over-simplification, it is useful to think of these trends as different s-curves – Figure 1.

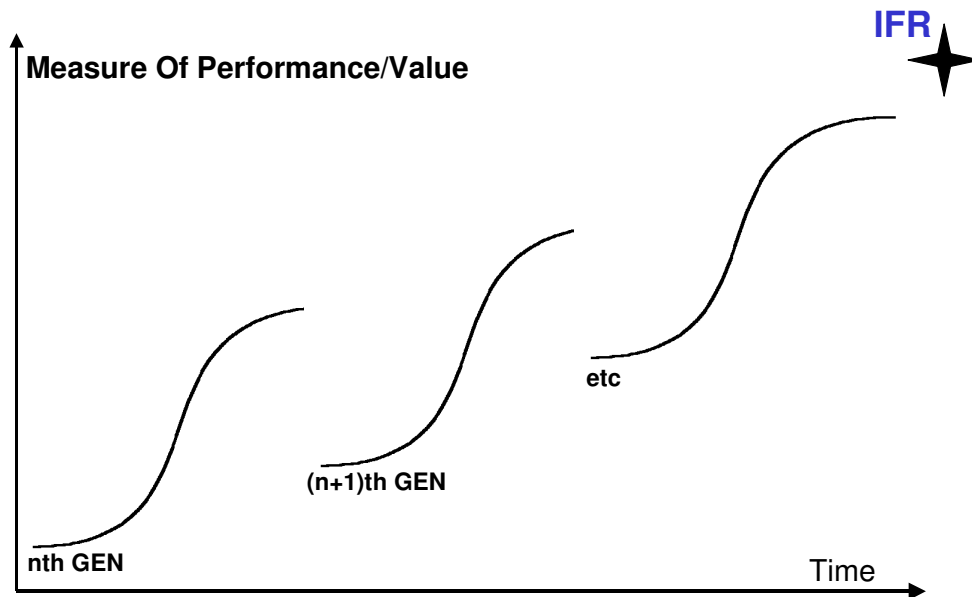


Figure 1: The Fundamental Dynamic Of System Evolution

The evolutionary s-curve drives the evolution of all systems. The research into evolution dynamics has also shown that all successful innovations possess an attraction to an ideal end-state. That end-state – typically defined as ‘Ideal Final Result’ (IFR) – is that the system delivers the functions and benefits that a customer requires, without any cost or negative impacts. While this end-state might sound somewhat theoretical, there are many examples of systems and components that have evolved to such a state (Reference 3). What Figure 1 shows is that the dynamic of evolution towards this end-state occurs through a succession of s-curves. Key to the understanding of the overall dynamic is the recognition that all systems hit fundamental limits: The flattened profile at the top of an s-curve is not an indication that the market or engineers cease to be interested in improving a system, rather that something emerges to prevent those improvements from taking place. In other words a conflict or contradiction emerges and a system hits a fundamental limit as a consequence. The only way, then, to go beyond this fundamental limit is to find a new s-curve. Finding a new s-curve means resolving the contradiction. The 35 uncovered trends (there may be more waiting to be uncovered, but 35 is the current total) in turn represents patterns describing how those contradictions have been resolved.

The paper uses these 35 trends as the global benchmark against which compressor technology can be compared. The paper describes some of the main trends and then introduces the concept of evolutionary potential as a means of comparing the absolute maturity of a system against a global standard of discontinuous system evolution. Beyond this, the paper describes the analysis of two regions of the compressor technology spectrum to demonstrate that, despite the fact that many in the industry would assume that compressors

are a well-matured technology, even those designs pushing the state of the art have considerable untapped evolutionary potential left in them. Conversely, the paper also indicates areas where technologies are hitting fundamental limits. The combined implications of untapped evolutionary potential and evolutionary limits are summarised in a section of the paper discussing the best and worst places to devote future compressor technology R&D and intellectual property resources.

TRENDS OF EVOLUTION AND EVOLUTION POTENTIAL

By way of introduction to the form and content of the discontinuous trends uncovered during the innovation research, Figure 2 illustrates a trend known as ‘surface segmentation’. This trend describes the evolution of the use of the surfaces surrounding structures. According to the trend, when engineers and designers first configure a system it is likely to feature a smooth surface. Then later, 2-dimensional grooves or protrusions of some description are added. The reason why such a jump occurs changes across different industries – so that in some it will be to reduce drag, or introduce a space for a lubricant or other material, in others it will be to increase surface area to aid thermal management, and in yet others it will offer the potential to improve grip or traction. The jump from smooth to ribbed/grooved, however, is consistent across all of them. Likewise, the jumps to the next stages of the trend – 3-dimensional and then active surfaces – are common across different industries, but for shifting reasons. Also shown in the figure is a typical design of piston from a piston-type compressor. As may be seen from the figure, this design has evolved to the second of the four possible stages.

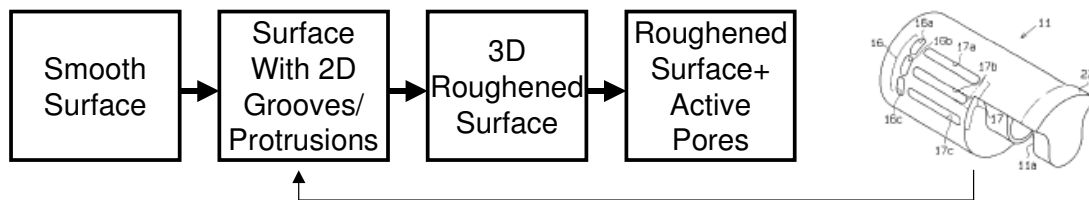


Figure 2: ‘Surface Segmentation’ Discontinuous Evolution Trend And Typical Piston Design

The main idea suggested by the trend, then, is that systems generally evolve in a left-to-right direction, becoming ‘more ideal’ at each stage. So, concerning the piston, which has only used two of the four possible stages, there is the suggestion that somehow the incorporation of 3-dimensional and active elements would be beneficial. Again the important idea is that the jump from one stage to the next represents a discontinuous shift from one way of doing things to another. Occasionally systems will evolve ‘the wrong way’ along a trend. There are a number of underlying reasons why this might happen – all of them so far predictable. The most common reason for a backward jump is that a backward step in along one trend is (in the short term) necessary to facilitate a forward jump along another – more important – trend.

Thinking specifically about compressor technology, as we have seen, typical piston designs have evolved to the second stage along this surface segmentation trend, while the rotors in a screw-compressor are still predominantly found at the first (‘smooth surface’) stage. The reason why the piston has made the advance is due to the demands of effective sealing and consistent lubrication. Nevertheless, according to the trend, because the screw

compressor rotor is likely to be still at the first stage, it possesses considerably more untapped potential. As the demands on these compressor types continue to evolve, they are highly likely to have to use up the unused surface segmentation potential in order to achieve the desires that engineers require from them. These desires may have nothing to do with sealing or lubrication of course – in which case the evolution to 2D or 3D grooves/protrusions is likely to occur for other reasons. Like for example in this specific case to achieve lower flow resistance or improved noise properties.

Figure 3 illustrates another of the trends, this time the one known as ‘dynamization’. This is a trend concerned, as the title suggests, with the way in which things move relative to other things. Again the trend is drawn in such a way that systems evolve in a left-to-right direction, with each stage representing a discontinuous advance on the preceding stage.

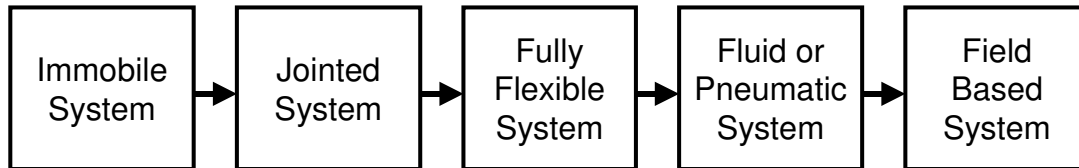


Figure 3: ‘Dynamization’ Discontinuous Evolution Trend

Here is another trend with direct relevance to the evolution of a wide range of different compressor types. This time, however, it is necessary to think a little more abstractly to connect between the design of a compressor and a stage on the trend. Pistons translate along their host cylinder, but yet the majority of them would be classified at the first ‘immobile’ stage of the trend. The important connection here – and an indication of the way in which the best advantage can be made of the trends – is that there is *some* aspect of a component that is immobile. A piston consisting of a single-piece would be classed as ‘immobile’ since the structure is designed to be as consistently stiff as possible. The same ‘immobile’ stage may also be seen in both screw and scroll type compressors. Examination of the valve-plates in refrigerant compressor designs, on the other hand, reveals that here is a part of the system that has evolved to the ‘completely flexible’ stage of the trend.

The fourth and fifth stages of the dynamization trend are more difficult ones as far as compressor evolution are concerned. If a compressor design is at any of the first three stages of the trend then, according to the evidence from other industries (which is where the trend has ultimately come from) it has two stages of untapped potential remaining. Both of these jumps are, however, comparatively large ones – away from mechanical to fluidic and ultimately field-based methods (where ‘field’ is intended to signify any type of field – whether it be electrical, magnetic, gravitational or any other connection that a user can make from the deliberately generic label). In both of these cases, current technological limitations prevent compressors from making the jump (but the trend has given us a good indication of where enabling technology research would be well-placed). In refrigerant compressor systems, however, we are already beginning to observe solutions that are eliminating mechanical components in favour of ‘field-based’ cooling systems – e.g. Peltier Effect based cooling devices. The jump from left-to-right in this case is occurring because field-based systems tend to be inherently more reliable, more controllable and less noisy. At least these are the reasons why the jumps have occurred in other sectors.

In reality, these two trends, and the other 33 presently known, all operate in an integrated fashion. The ‘evolution potential’ concept is a means of observing the trends together. Their

basic principle of operation is very simple: In order to examine the overall evolution potential of a system, it needs to be compared against each of the trends in turn. As we do this we will soon discover that some of the trends cannot be connected to the system. Such trends are deemed to be not relevant – typically, in fact between 10 and 25 of the 35 will be useful in analyzing any one system. The non-relevant trends (which will shift from one application to another) are eliminated from the analysis. Each of the remaining ‘relevant’ trends is then compared to the system under evaluation and an assessment made of how far along the trend a system has reached.

Thus, if the valve-plate of a refrigerant compressor is under evaluation relative to the ‘surface segmentation’ trend, a state-of-the-art design will be at stage 2 of 4 possible stages. Likewise, relative to the ‘dynamization’ trend, a state-of-the-art valve-plate will be at stage 3 of 5. Repeating this process for each trend in turn, and then arranging each trend as one spoke on a radar plot reveal a picture of the overall current evolutionary state of the valve-plate. The basic idea is illustrated in Figure 4.

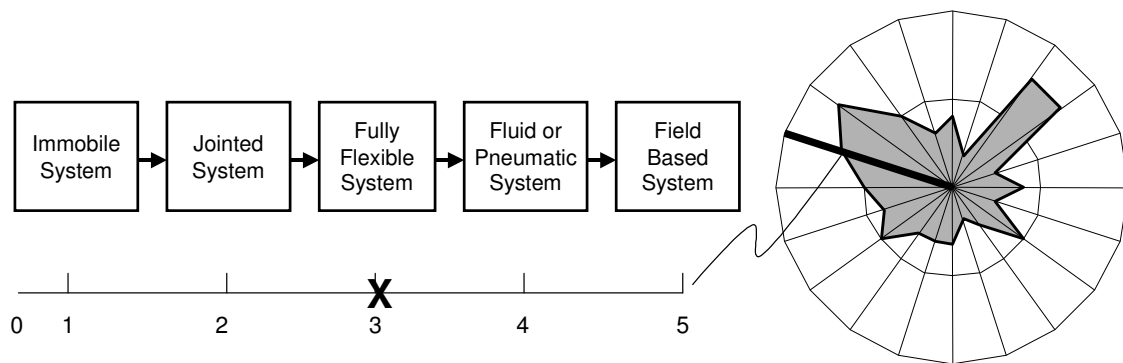


Figure 4: Evolution Potential Radar Plot Structure

The perimeter of the radar plot represents the frontier of engineering knowledge against each of the known trends. Thus the empty space between the current evolutionary state of the system described by the shape at the centre of the picture and this perimeter represents the untapped potential of the system. If, therefore, there is a desire to improve some aspect of a current system, the trend lines and the untapped potential act as signposts indicating the directions that other successful systems have evolved in.

It is almost impossible to convince anyone that *all* of the jumps on *all* of the trends lead to better designs in *every* area, on *every* occasion. In twelve years of using the trends, however, this author has not found a single exception. This despite having a full-time research team of some 25 people who spend every day examining new inventions in an attempt to disprove the known trends and to find new trends. Sometimes we aren’t smart enough to work out why a jump should take place, but inevitably over the fullness of time we will see that reason becoming apparent. Whether or not people ‘believe’ the trends – and it is certainly not the purpose of this paper to attempt such a feat – at the very least they should be viewed as a potent way of focusing and directing short cuts to better solutions. In part this is where the term ‘systematic innovation’ – the emerging name of the overall methodology surrounding these trends – comes from.

In the next two sections we will explore some of the attributes of the evolution potential concept as they relate to two different compressor types. We will begin this exploration with a look at the evolutionary history of screw compressors:

EVOLUTION OF SCREW COMPRESSOR SYSTEMS

Given the basic evolution potential ‘global benchmarking’ concept and the radar plot format, it becomes possible to use the capability in a number of ways. Examining the various generations of design of screw compressor systems in the industry and overlaying the plots for each, it becomes possible to see how quickly the evolution potential is being used. Figure 5 illustrates such a composite picture highlighting the jumps that have taken place from the first screw compressors to the most recent.

The plot labeled ‘1’ describes the evolutionary state of the first generation screw compressors as defined by German patents from the latter half of the 19th Century. In simplified terms, then, stage ‘2’ represents the evolution of the first twisted rotor geometries of the Heinrich Krigar patents, also on the late 1800s. This evolution is shown as an advance along another trend of evolution known as ‘geometric evolution’ (Reference 2 provides more details on this and all other trends). We see further geometric advance in the 1930s designs of Ljungstroms Angturbin AB in Sweden when inventor Alf Lysholm developed the profile of the screw compressor and tested various configurations and rotor lobe combinations. Not only was the shape of the rotors important, he solved the problem and patented the method for accurately machining the rotors – shown in the radar plot as an advance along the ‘macro-to-nano’ scale trend. Lysholm’s 1935 patent clearly shows his asymmetric 5 female - 4 male lobe rotor design. Although the shapes have been ‘fine tuned’ over the years, the ‘modern’ screw compressor saw its birth at this point. The fourth stage highlighted on the plot represents an amalgamation of the miscellany of smaller evolution jumps that have taken place in more recent times. Shown at this fourth stage, then, are things like the incorporation of balance pistons to improve life by compensating for side loads on bearings, variable geometry porting to improve off-design performance, thrust compensation controllers (‘controllability’ trend) and assorted other secondary performance enhancing features.

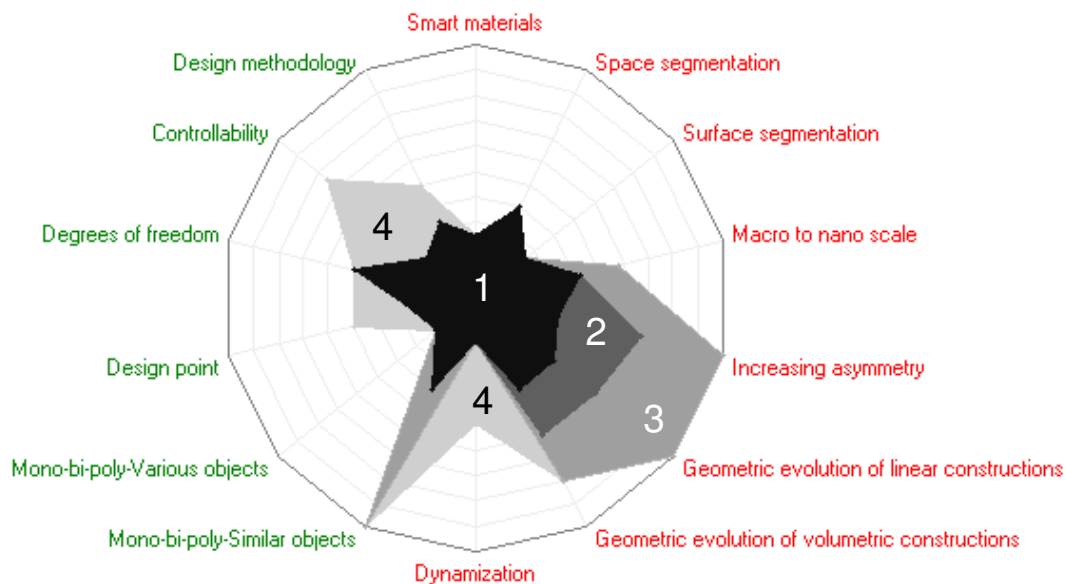


Figure 5: Evolutionary History Of Screw Compressor Technology

What is perhaps most interesting about the current evolutionary state is the amount of remaining untapped potential still available. Undoubtedly screw compressor technology may be seen to be mature in terms of geometric evolution – once all of the available dimensional

freedoms have been used, there is nowhere else to go. Looking beyond geometry, however, and the plot shows there is still considerable potential for future improvement along a number of other evolution trends – the previously discussed surface segmentation trend included.

It is beyond the scope of this paper to explore this untapped screw compressor potential. What can be said with some confidence though is that each unused trend represents opportunity for not only the step-change improvement in some aspect of the design of the compressor, but perhaps more importantly, in the direction of future research and the generation of new intellectual property.

EVOLUTION OF REFRIGERANT COMPRESSOR SYSTEMS

Figure 6 takes the evolution potential radar plot to a different level. A single high-level plot for a typical state of the art refrigerant compressor has here been complemented by equivalent plots for some of its main constituent parts. One of the values of conducting such an exercise is that it allows R&D strategists a clear, objective picture of which components within the system have more untapped potential than others. If we find ourselves working in an environment where there is insufficient funding available to do everything, then here is a way to help focus money into those areas that are likely to deliver the biggest benefit per unit of capital invested. A precise analysis, of course, requires rather more detail than we have the scope to describe here, but hopefully the point is made that the objectivity of the evolution potential concept certainly lies at the heart of such an analysis.

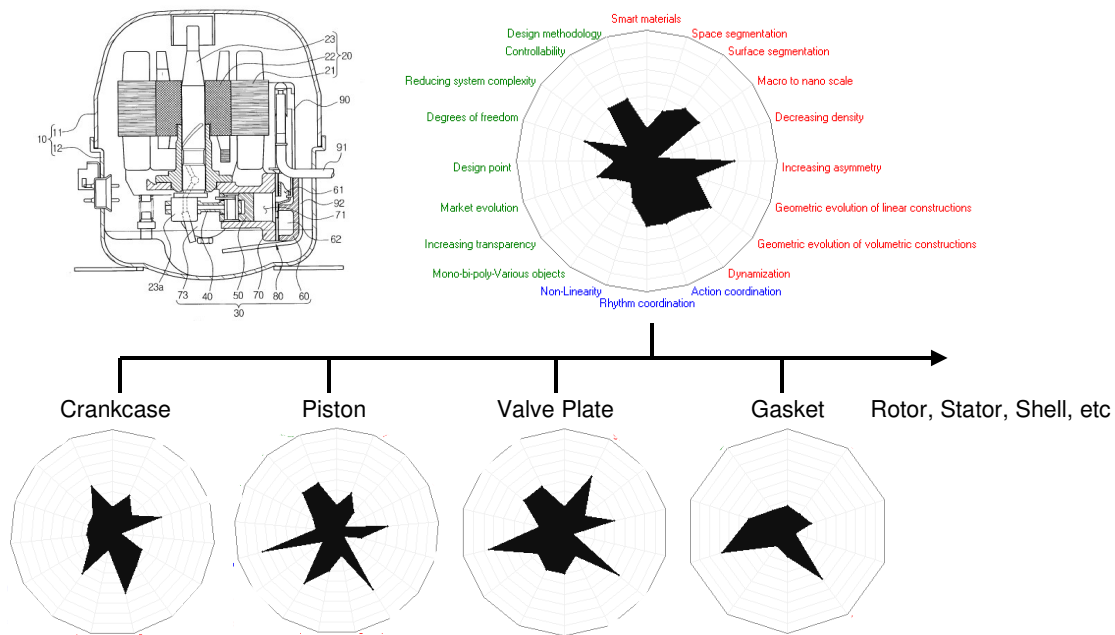


Figure 6: Evolutionary Potential Of Typical State Of The Art Refrigerant Compressor

In addition to acting as a ‘global benchmarking’ tool, the more important function of the evolution potential concept is as a structured means of generating useful product evolution ideas. The information used to compile the Figure 6 plots comes from a discussion of the prior art to US patent 6,835,050, granted to Samsung on December 28 2004. The plots in this case suggest the considerable untapped potential in just about all of the components present in the design

The motivation behind the Samsung invention was a desire to reduce noise and improve efficiency of the system. The key inventive step in achieving the inventors' solution involves the incorporation of a groove in a gasket component. This inventive step is shown in Figure 7. Alongside the isometric view of the new gasket is the corresponding evolution potential radar plot for the new gasket overlaid onto the original plot found in Figure 6. What this figure then shows is that the essence of the Samsung invention corresponds to a single stage jump along the previously discussed surface segmentation trend. Every other aspect of the gasket is evolutionarily identical to previous designs.

Clearly there was rather more effort required by the Samsung inventors than simply adding a groove to one of their gaskets, but a key point worth thinking about here is that an invention that first appeared only a matter of months ago had been signaled by a discontinuous trend of evolution that has now been in existence for over 40 years. The surface segmentation trend – like all of the others – represents the voice of the product. Having identified that gaskets are smooth-surfaced things, the trend is trying to tell us that 'somewhere there is a benefit in adding some kind of groove or protrusion into the design'. The trend has absolutely no idea how, where or why to do so, merely that based on the successes of others in other industries, that benefit will be present somewhere.

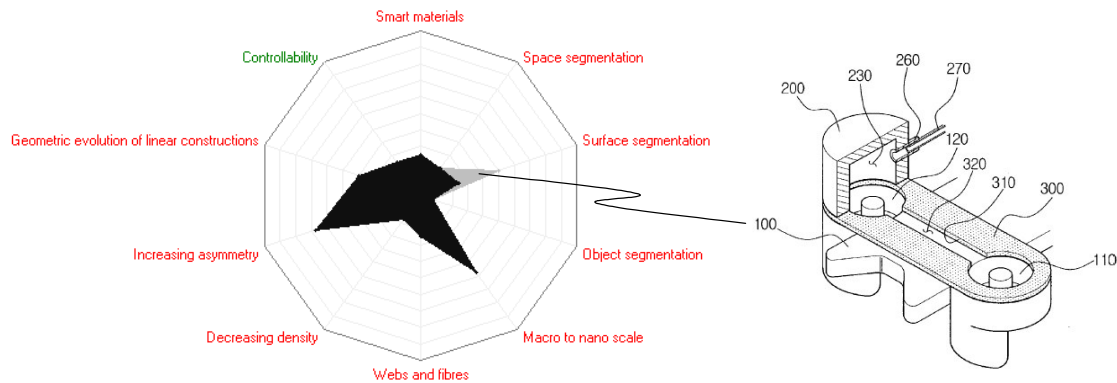


Figure 7: Evolutionary Comparison Between US6,835,050 And Prior Art Gaskets

The trends of evolution do not exist to replace anyone's creativity, but instead merely to try and direct it along profitable paths. The Samsung design has made a single jump along a single trend, but as can be seen from the new radar plot, there is still a mass of untapped potential. Having made one jump, the surface segmentation trend is still suggesting the likelihood of two additional advantages by adding more grooves, making them 3-Dimensional and adding something active into them. All of the other trends are similarly suggesting a host of other currently untapped potential, not just in the gasket but, as can be seen from Figure 6, in every other component in the design too. Any one such jump may well result in the creation of a patentable solution.

ACCELERATED EVOLUTION – IMPLICATIONS AND OPPORTUNITIES

The real issue here is to think that it took until so recently to make this simple jump. Had other companies been thinking about the trends of evolution in general, and the surface segmentation trend in particular, it is interesting to speculate on whether they would have made the connection that Samsung recently did. Irrespective, though, of whether Samsung actually chose to incorporate such a design into one of their systems, an evolution potential

analysis would have allowed them to at the very least recognize and protect the idea so that none of their competitors could have used it. This connection to the generation of IP is probably the most important aspect of all when the implications of the discontinuous trends of evolution uncovered during the systematic innovation research are considered.

The discontinuous trends offer the potential to considerably accelerate the evolution of systems (References 4 and 5). Every unused stage on the screw compressor or the Samsung refrigerant compressor design or any other compressor system we may care to put under the spotlight represents the opportunity to design a better system. The trends encourage designers to ask new questions when they are designing any kind of component. As suggested in Figure 8, by comparing our current system with each of the trends (in this case ‘dynamization’ has been used as an example again) and making a connection with one trend stage, all of the unused trends stages to the right of that connected stage represent potential solutions. We may not know what problems such jumps might solve yet, simply that based on what other successful inventors and problems have found, somewhere, somehow there is an advantage in moving from left-to-right.

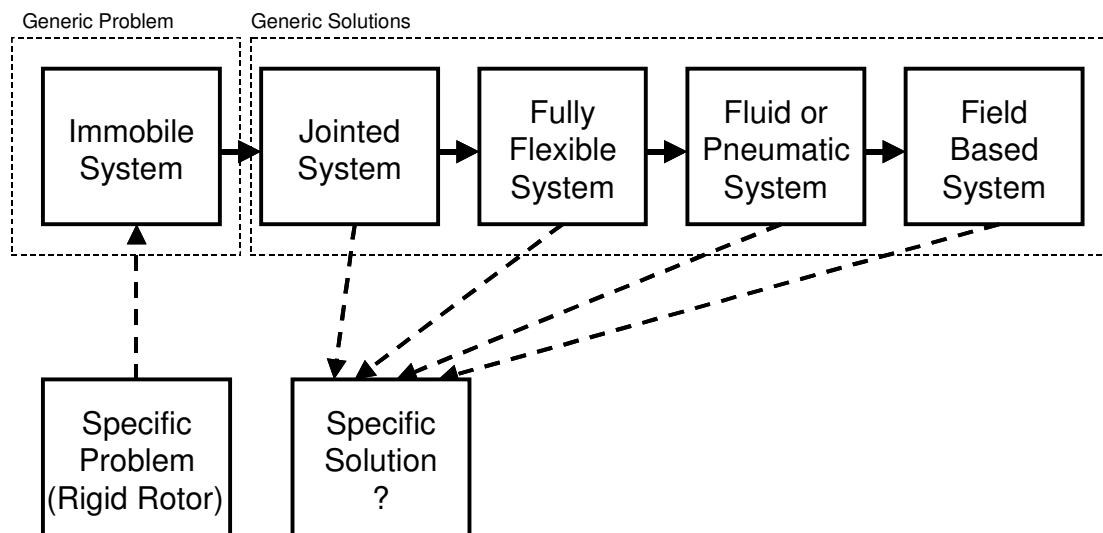


Figure 8: Trends As Evolution Sign-Posts

One of the big ideas in systematic innovation is that someone, somewhere already solved a problem like yours. The trends represent a summation of the general directions those previously successful problem solvers have taken.

SUMMARY

- 1) The systematic innovation methodology has uncovered some of the underlying fundamentals of system evolution: successful systems evolve through a series of discontinuous jumps in a direction towards an Ideal Final Result end-state.
- 2) The same generic jumps may be seen to occur across different industries. By using the jumps that other industries have already made, it is possible to accelerate the pace of innovation in others. The implications of the possibilities opened up by this accelerated knowledge transfer – particularly in relation to IP issues – are potentially profound. Historically, organizations have not been very good at making step-change innovations

(Reference 6). It may still be true. The difference now, however, is that at least they can see what is coming, and take the necessary avoiding steps.

- 3) Comparison of compressor technologies at two different points along the industry spectrum reveals that in some areas, the high-end technologies have hit some fundamental limits in relation to some possible evolution directions. At both ends of the spectrum, however, there remains considerable untapped evolution potential when comparing to the global measure of evolutionary possibility. The implications for the industry as a whole may be expected to be significant on both counts.

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