Choosing the most promising system evolution paths with TRIZ – Rebar Tying Case Study

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Abstract

One of the oft encountered problems while applying TRIZ to real world problems is to identify from a large set of promising solution directions, the ones that are most promising, elegant or closest to ideality. This is especially true when the problem can be defined at multiple system levels, each level having multiple paths flowing towards the ideal final result. This paper describes such a situation encountered while analysing a real world problem (rebar tying) with TRIZ. Steel reinforcement bars are tied together to form grids and reinforce concrete. Rebar tying machines have evolved over the years from pneumatic and mechanical systems to electromechanical systems with embedded electronics. TRIZ-based analysis and ideation resulted in a large number of interesting evolution paths for the rebar tying system. However, the question "Which paths would evolution favour" was difficult to answer. TRIZ does offer clues to preselect the most promising paths in advance, but needs an integrated approach for the same. The paper describes such an integrated approach with the rebar tying case study as reference.

Rebar Tying – Background and Evolution

We have all seen at our construction sites these huge grids of steel bars; concrete is poured over these bars to create huge concrete slabs of various shapes and sizes. These steel bars are reinforcement bars (rebars in short), used to reinforce the concrete and improve its tensile strength.

During the creation of rebar grids, rebars have to be tied to ensure that they do not get displaced when concrete gets poured over the grid. Displaced rebars do not optimally contribute to tensile strength.

In the developing world, the rebars are tied manually using a pair of pliers (quite a monotonous and back-breaking job!). In the developed world, rebars are tied with specialized "rebar tying machines" as shown in the adjoining picture. Tool manufacturers are constantly attempting to improve the tool and make it faster, better, cheaper. Predominantly, there are four key parameters that the rebar tying tools attempt to improve –tying time (or effort), worker ergonomics, tie strength (function) and tie length (related to cost).

Understanding the rebar tying context

A first look at the rebar tying tool ecosystem using the Nine Windows (only the past and the current) reveals:

Brick and mortar, cement Different types of knots for varying applications and tie strength requirements Manual and mechanical methods of tying No reinforcement bars	 Concrete used in construction Tying as a subset of holding together (other mechanisms like sewing, zipping, gluing, stapling, riveting, crimping, welding, electromagnetism etc.) Tying as a function (tying different types of objects other than rebars – cables, luggage, plastic bags, packaging) Rebar ecosystem Steel rebar grids Rebar cutting and bending tools Rebar stands 	?
Manual tying with pliers	 Rebar tying machine The process of rebar arrangement and tying (engage-feed-wrap-cut-tie-disengage) 	?

Table 1 Rebar Tying - Nine Windows

Mechanical, spring-	•	Type of feed (uncut wire, cut wire,	?
based or pneumatic		clips)	
	•	Engagement mechanism	
	•	Feed mechanism	
	•	Bending mechanism	
	•	Wrapping or binding mechanism	
	•	Cutting mechanism	
	•	Tying mechanism	
	•	Tool structure	
	•	Electromechanical and electronic	

Patent trends





The 1970s saw incremental improvements in essentially mechanical (spring based) mechanisms for wire guiding and tying. Electrically powered tools (US Patent 4362192) were introduced in the 1980s. Some efforts were made to make a tool adaptable to various dimensions of rod cross-sections (US Patent 4542773). In the late 1980s electric logic circuitry was introduced to control the tying operation (US Patent 4953598). Attempts to get a stronger tie were made through mechanisms to remove wire slack and usage of feed rollers (US Patent 4953598). A tool capable of adapting to various dimensions of rebar cross-sections was also introduced. Electromagnetic control mechanisms for specific tool sub-systems were introduced in the mid-1990s (US Patent 5217049). The late 1990s saw a spate of inventions - control mechanisms such as prevention of wire entanglement and wire disengagement by monitoring and controlling motor torque (US Patents 5831404, 5874816), reduction of slack while twisting (US Patent 5826629), spring based safety device(US Patent 6601766) for different rebar diameters was introduced in the early 2000s. Plastic tie fasteners (US Patent 6503434) were also experimented with. In the recent past newer mechanisms for precision control have been explored. Photo and colour sensors have been used

in multiple inventions (US Patent App 20070227613) along with RF tag readers, rotation detection sensors (US Patent App 20080134908) and magnetic sensors. Heat sensors have been used to control tool operation and prevent failure in the case increased temperature within the tool due to continuous usage (US Patent 7353846).

The wire material has not seen too much change. Plastic tie fasteners were experimented with in the early 2000s. A recent patent describes a textured wire tie (US Patent 7250213).

Ideation

System Contradictions and Inventive Principles



Figure 2 Why-Whats Stopping Analysis

Reinforcement bars are needed to increase the tensile strength of concrete. The bars need to be tied together to prevent them getting displaced when concrete is poured over them. Manual tying, as several reports testify, is literally a back breaking process. The primary purpose of the rebar tying tool is to enable the worker to remain in ergonomically safe positions during the process of rebar tying. Also, faster tying enables improved productivity and reduced fatigue. A study conducted by the Construction Safety Association of Ontario in September 2004 came out with the following findings [9]:

	Manual Tying	Automated Tying using a Rebar Tying Tool
Average Tying cycle time	8.9 s	4.2 s
Wrist loading	High risk	Low risk
Lower back loading	High risk	Low risk

Table 2 Manual vs. Automated Tying

Note: The tool specifications (from tool vendor websites) mention tying time between 0.9 - 1.1s. We have to assume, therefore, that the 4.2s above includes tool positioning and tool disengagement times as well.

Machine ties also ensure uniformly consistent tie quality (as opposed to manual tying which is prone to decreasing quality related to fatigue). The rebar tying tool certainly solved a number of problems associated with manual tying.

However, several unresolved contradictions continue to exist. For example, increased tie strength requires complex ties and tying mechanisms, adding to device complexity and weight of the tool. Simple tools are unable to make strong ties, thereby increasing the possibility of rebar displacement. Increasing tool adaptability to different rod diameters, rod shapes and rod intersection angles has a detrimental impact on tie strength and device complexity. Increase in device complexity increases device failure rates and device repair times.



Figure 3 System Contradictions

What follows is a sprinkling of some of the most interesting ideas generated from the solution directions recommended by the inventive principles:

- 1. Usability Design
 - a. *Local Quality, Pneumatics*: Rotating handle (rotated manually with a finger) to control tie strength;

- b. *Dynamics*: Fibre handle similar to endoscopic devices; flexible and rigid as and when required to reach hard to access joints
- c. Counter weight
 - i. movable tool support for vertical grids
 - ii. tool balloon/kite/para-sail (for high places, also helps find where the worker is)
- d. Nested Doll: Spherical telescopic tool for improved ergonomics
- 2. Universal Tool
 - a. *Dynamics*: Tool grip with adjustable gripper, grip force used to modify shape and tie strength
 - b. Self Service: Tool handle, that can recharge battery with twisting action
 - c. Self Service: Battery recharged during tying action
 - d. Universality, Dynamics
 - i. ability to detect diameter of rebar and adjust tie length and tool dimensions
 - ii. knot remover
 - iii. ability to choose different types of ties
 - iv. ability to use continuous wire, precut lengths and clips
 - e. Merging
 - i. one motor for feeding and tying
 - ii. rotating clip as a wire transport mechanism
- 3. Segmented Tool
 - a. *Segmentation, Dynamics, Local Quality*: Clip-on tool sections, reduces weight all sections are not required all the time
 - b. *Segmentation, Dynamics*: Jaw section to have max weight; remainder of the tool connected by flexible wire no weight during tying , jaw movable with respect to tool
- 4. Remotely Operated Tool
 - a. Mechanics Substitution: Wireless enabled tool
 - b. Remote screen-based operation
 - c. *Segmentation*: Multi person operation one to clamp the joint, other to remotely control the tie
 - d. *Mechanics Substitution*: Detect tie strength remotely using infrared, ultrasound
 i. for the entire rebar grid via a 2-D or 3-D map
 - e. Multiple ties use minimum force for initial tie, second stronger tie wherever required
- 5. Sensors and Feedback
 - a. Sensors
 - i. Detect stress level of wire
 - ii. Pressure gradient sensor
 - iii. Detect rupture/ breakage

- iv. Detect shape change
- v. Colour changes: Coloured wire to indicate end of wire, mark diameter length sensor to detect colour change to control the tying action
- b. *Feedback*: LED on the tool to indicate sensor feedback to user e.g. too tight, too loose etc.
- c. Partial or excessive Action: Slip mechanism post tie to avoid excess force
- d. Dynamics: Knot strength adjustable at run-time manual and automated
 - i. Mechanism to transfer power from hand to jaw tighter the grip stronger the tie
- 6. Pulsations/ Vibrations
 - a. Mechanical Vibration: Blinking LED for error detection
 - b. Continuity of Useful Action: Beneficial action between pulses
 - i. Adhesive introduction
 - ii. Pre-stress the wire
 - iii. Pulsating tying action similar to squeezing water out of a cloth
- 7. Type of Wire/ Clip: Composite Materials
 - a. Two sided wire
 - i. Flat side for holding the rebars, round side for tying
 - ii. Inner flat surface outer ribbed surface
 - b. Different cross-section say square or hexagonal
 - c. Two layered wire one strong, one slightly less strong
 - d. Thinner wire threads and multiple ties
 - e. Serrated wire like baggage clips
 - f. Hollow wire micro-hose
 - g. Porous wire, soaked in adhesive

Laws of System Evolution

System

A preliminary analysis of patents reveals that the key Laws of evolution of the rebar tying tool have been the Law of Completeness and the Law of Shortening of Energy Flow Path. While the binding force has remained mechanical, the controlling forces have evolved from mechanical to electromagnetic stage.



The need for increasing functional flexibility is clearly apparent (tools capable of adapting to a wide range of rebar diameters, tie types (wires and clips), tie diameters, tie textures etc. We can expect the rebar tying tool to become more modular and segmented with programmable subsystems. For example, one could replace the clip cartridge/ wire reel and the jaw, depending on the diameter of the rebar. The tool can come with a set of jaws and cartridges of multiple sizes (exactly like our multi-screw driver kit). The tool can be configured on the spot for vertical or horizontal tying or for tying specific types of knots. The tool can also operate in multiple states (high precision and low precision, high speed and low speed etc.



Increasing functional flexibility will further drive the transition to higher level systems in the form of poly systems and increasing diversity of components. A multi-jaw tool with configurable jaw positions can be used to tie different types of knots (saddle tie, diagonal tie etc.).



Current rebar tying tools are already versatile enough to tie electric cables, wires etc. The universal binding tool of the future will include multiple binding mechanisms (tying, stapling, clamping, sticking) to bind a variety of objects.

The rebar tying tool is also likely to become more physically flexible to aid accessibility in different configurations of rebar grids and rebar types.





At the same time, some systems may convolve or be trimmed e.g. Clip ties are a step in this direction. Clips are pre-cut and pre-bent, therefore two entire sub-systems (cutting and bending) are eliminated. Furthermore the complexity of guiding and tying mechanisms is reduced.

Clips also offer the possibility of a more radical convolution and simplification of systems in the form of elimination of the rebar tying tool itself. The adjoining speed-clip [US7377083], applied by hand, can bind rebars securely in a cycle time of close to 1 second. This is comparable to a machine tie (this product won the 2005 World of Concrete 2005 Most Innovative Product Award). Also, since the clip application process is fairly straightforward, a long handled set of pliers (or a specialized handle) can potentially be used by workers to apply the clip from a standing (non-bent) position. For vertical ties, the speed clip may be a simpler mechanism as

compared to tying with a rebar tool (considerable reduction in weight).

The above was an instance of transition to a higher level system and a higher degree of Ideality within the same system level through convolution of systems. The transition to higher level system can happen at the super-system level as well.

Super System

Reinforcement bars themselves are likely to become more fragmented (surface as well as volume). A change in rebar material from metal to polymer-based (e.g. Glass Fiber Reinforced Polymer rebar) can accelerate the fragmentation trend (both surface and volume). Surface fragmentation can happen in the form of small cliffs and troughs further provided with a sticky coating, or made slightly deformable so that weight of concrete further strengthens and reinforces the rebar joint. Volume fragmentation could be in the form of hollow or perforated rebars.

Along the Law of transition to micro level, reinforcement bars can move from macro to micro level, in essence, instead of a mega grid of reinforcement bars, there will be micro-grids of thinner reinforcement bars. Maybe the need for a grid may vanish, concrete slurry could contain numerous micro reinforcement chips or filings, all automatically aligned (maybe with the help of a magnetic field) to provide maximum tensile strength right through the concrete mix.



Moving to a further super system, concrete itself may evolve along the line of increasing fragmentation and the law of transition to micro-level.



Air-entrained agents have been in use since the 1930s [8]. Air-entrained concrete contains billions of microscopic air cells. These relieve internal pressure on the concrete by providing tiny chambers for the expansion of water when it freezes. Similarly, it is known that the fire performance of concrete can be improved by mixing high strength concrete with recycled rubber

material [7] – this reduces the risk of explosive spalling of concrete at high temperatures because water vapour can exit through the channels left as the polymeric particles get burnt. The next stage is for the pores to be filled with active agents for various purposes (strength, adaptability, weight etc.).

Considering the recent advances in micro and nano-technology, the area of concrete admixtures is likely to be a hotbed of inventions in the near future.

Evaluating and selecting ideas

We create a smaller subset of idea combinations from the larger list as follows:

1	Flexible Handle with	The tool handle has a grip with a pressure gradient sensor to	
	Intelligent Gripper and	sense the grip pressure. The tool jaw also has a pressure gradient	
	Pressure Gradient	sensor to detect strength of the tie. The handle is flexible to	
	sensors	enable easy access to rebar intersection points. The user can	
		adjust tie strength by compressing the tool grip.	
2	Spherical Telescopic	The tool is built to have the most efficient weight distribution	
		while tying as well as during idle times (moving from one tie to	
		another) with the use of telescopic parts (handle, jaw etc.)	
3	Universal Segment-able	A universal modular tool with clip-on subsystems (wire reels	
	Plug n Play with	clins battery power different sized jaws etc.) The jaw can be	
	remote control	clipped on to an intersection by a worker and the tie mechanism	
		controlled from a remote location via wireless connectivity	
1	Pulsating tying with	The tool has a pulsating rotation mechanism to pre-stress the	
-	hattary racharga	wire remove slack, cut down on guiding engagement errors and	
	batter y recharge	raduce rick of the breekage. The pulseting extion is also used to	
		recharge the bettery	
5	Demons wine alin with	A notice d complexity tool achieves strong ties by combining	
Э	Porous wire ciip with	A reduced complexity tool achieves strong ties by combining	
	active adhesive	mechanical and chemical forces. A porous wire clip filled with	
		adnesive material enables simultaneous tying and sticking	
		together of rebars. The adhesive is released at a specific pressure	
		threshold. The clip can be affixed manually or by using a tool.	
6	Micro-rebars with	Concrete slurry contains micro-rebars. Based on the design of the	
	magnetic alignment	concrete structure, micro-rebars can be positioned to provide	
		maximum strength. Positioning is controlled using a magnetic	
		field.	
7	Air-entrained concrete	Concrete admixtures consist of micro and nano strengthening	
	with micro-	agents. These agents enable multiple aspects of concrete	
	strengthening agents	strengthening. Some agents coat the air entrainment bubbles.	
		Others work as fillers. Some agents absorb or trap moisture or	
		create pathways for escape of water.	

Table 3 Idea List

Which ideas are the best ones? This is a multi-layered question.

- 1. Which ideas are in sync with S-curve dynamics? We can use patent information to plot Althsuller's S-curves of Useful Function, Harmful Function, Number of Inventions, Level of Invention and Profit, find the position of the current system on these curves and then select the ideas best suited to take the technology S-curve forward.
- 2. From whose perspective? We can evaluate these ideas from the perspective of multiple stakeholders, namely the end-user (worker), the tool manufacturer and the sponsor (building or road contractors).

Altshuller's S- Curves

From "rebar tying" patents [

Patent trends] and other relevant literature [8, 9], we can surmise the following:

1. Useful Function

- a. There has been a slow increase in useful functions (improvement in worker ergonomics, tie strength, tying time, tie length and adaptability).
- b. Tying time (total cycle time) has not reduced significantly. The tool tying time has been hovering at close to 1 second for a while now.
- c. Tie strength has improved only marginally over the same period. Most tools are capable of diagonal ties only (one of the weaker ties). Stronger ties like saddle ties are too complex.
- d. Tie lengths (amount of material used) have reduced marginally.
- e. Adaptability has been improving steadily. Earlier tools were able to work with only a small range of rebar diameters. This range has improved in recent years.

2. Harmful Function

The automated rebar tying tools had a significant impact on worker ergonomics as compared to manual tying with pliers by considerably reducing the risk of wrist and back injuries. Since then, complexity and cost has increased with only marginal reduction in injury risk.

Increase in tool complexity (number of mechanical, electrical and electronic parts) has actually introduced harmful functions (such as failures in wire wrapping and wire feed mechanisms). Further incremental inventions have been focused on correcting these errors. It is likely that further increase in functional flexibility (different rebar diameters, tie types, tie lengths) will trigger an increase in number of sub-systems with corresponding increase in tool size, weight etc. This may have a detrimental impact on worker ergonomics.

3. Number of inventions

The double hump trend is clearly visible in the patent frequency chart in **Error! Reference source not found.**



Figure 4 Mapping to Altshuller's S-curves

Mapping the technology trends to three of the five curves above [5], it seems that rebar tying tools are currently entering the **maturity** stage of the functionality curve. Future inventions on the same S-curve are likely to marginally improve the functional quality of the tool (efficiency, reliability etc.).

The best ideas should therefore, enable a transition to the next S-curve. We use the Analytic Hierarchy Process to evaluate the ideas from the perspective of "*Ability to initiate the next S-curve*'. The Analytic Hierarchy Process [10] uses a relative prioritization mechanism (pairwise comparison of alternatives with respect to a specific goal or set of goals) organized in the form of a hierarchy of decisions. The AHP is a powerful framework to objectively quantify decisions that are qualitative in nature.

We get the following relative ranking (the ranking is illustrative; opinions of different experts may vary).



It is important to note that the evaluation criteria will change based on the position of the state of the art on Altshuller"s evolution curves. For example, if the technology area had been in the growth phase, we would have to probably evaluate the ideas with respect to a near term objective of "Ability to Accelerate Growth" in addition to a longer term of objective of "Ability to initiate New S-curve".

Multiple stakeholders

The ideas are relatively ranked with respect to each perspective (end user, manufacturer and sponsor). Note: The rankings are based on illustrative scenarios. Actual end users, manufacturers and sponsors might vary in their opinions.

End User

The end user is the worker who uses the tool on a daily basis. His primary requirement is comfort – a tool that enables good ergonomics and is easily adaptable to various tying contexts. However, elimination of the tool may not be something he looks forward to in the near term; this would require him to learn new skills to earn his daily livelihood and while this may open up

better opportunities for him in the future, he would prefer not to disturb status quo too much.



Manufacturer

The tool manufacturer has invested in tool R&D. He is interested in meeting the needs of the tool end-users (ergonomics) as well as his customers (construction companies) while simultaneously ensuring maximum Return on Investment. He would like to build incrementally on his current models (that are widely used in the market and are trusted by the customers) to provide more and improved functionalities at higher profit margins. He wouldn't like a situation where his tool becomes redundant.



Sponsor (Construction Industry)

The construction company looks at overall costs of materials and operations, quality of structures and ease of manufacturing, design and execution. He is also looking at supply chain efficiencies. Other than core parameters of strength and adaptability of concrete, he is also driven by cost of materials and labour and speed of execution.



Consolidated Ranking

It is prudent to assume that the future of rebar tying technology will be influenced in equal measure by each of the stakeholders as well as the evolution trends of technology itself. We therefore assign equal weightages to each of these perspectives to get a consolidated picture.



Conclusion

Technology evolution is a complex process. Multiple forces operate simultaneously to determine the course of evolution at any given point in time. Decisions are driven by business and technology drivers, system and super-system trends, strategy and tactics, collaboration and competition, emotions and intelligence.

In the case of rebar tying tools, technology has been evolving incrementally over the past several years. Patent trends indicate that the system is in its maturity phase. Ideas generated using TRIZ contradictions and inventive principles, laws and lines of system evolution include a number of system and super-system ideas.

TRIZ in combination with The Analytic Hierarchy Process provides an active, yet neutral canvas to create a common operating picture to evaluate these ideas. Althsuller's System Evolution Curves can be used to evaluate ideas on the basis of their impact on the S-curve dynamics of the technology area in question and closeness of the ideas to the Ideal Final Result. Given that the rebar tying tool system is in maturity phase, the super-system ideas seem more likely to initiate the next technology S-curve.

The best evolution paths, technically speaking, may not be unanimously agreed upon as the most attractive paths by the various stakeholders involved. Needless to say, each stakeholder has his own set of criteria for evaluation. Using the AHP, ideas can be evaluated from the perspective of multiple stakeholders. In the rebar tying case, the AHP based consolidated rankings indicate a near term tug of war between system and super system ideas, with the super system ideas prevailing in the long term. The end user and manufacturer loyalties are likely to remain with the system level ideas while the sponsor might enjoy action on the super system ideas. This is an interesting reflection of ground realities that impact the direction and pace of evolution. Will a disruptive super system innovation (concrete material with strengthening agents) make the rebar tying tool redundant in the near future? We will have to wait and watch.

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