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Value Engineering and Function Analysis: Frameworks for Innovation in Antenna Systems

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Abstract: Value engineering (VE) and function analysis (FA) are technological tools for the functional enhancement and cost reduction of engineering projects. They also help to overcome mental inertia by acknowledging the voice of the customer in complicated systems. Antenna engineering, providing electromagnetic remote links, is an important area in engineering science, with a large number of innovative concepts. However, managing innovative ideas to improve performance, reliability, quality, safety, and reduce life cycle costs, is still a work in progress. This research was designed to apply VE and FA as frameworks for innovative ideas in antenna systems, especially with regard to imaging and radar systems. FA diagrams free a designers' mind from tools to instead focus on purpose, which can help them to obtain better ideas for solutions to problems. It was identified that there were several options available for functionality enhancement and cost reduction. The required functionalities of the components of antenna systems, and their advantages and limitations were indicated. In addition, it was identified that some of the advantages and limitations appeared for combinations of the components. Alternative methods for applications, such as polarization conversion and the separation of outgoing and incoming electromagnetic waves, were studied. Circular polarization (CP) is important for two-way communication, since left-handed circularly polarized waves usually return with right-handed CP from targets. Therefore, various methods for producing CP were discussed, such as metamaterial-based linear to circular polarization converters and waveguide polarizers. Also, potential extra applications for these systems were explained. Two examples were: (1) merging multiple systems with different operating frequencies using multiband components; and (2) applying a feeding system for multiple reflectors using surfaces that reflect half of the wave and transmit the other half. Consequently, it was identified that the clearance of existing functions, prioritization of customers, identification of system bottlenecks requiring innovative methods, and better communication between users and designers, were the key benefits of VE and FA.

Keywords: function analysis; value engineering; inventive design; antenna systems; antenna design

1. Introduction

Engineering systems involve functionalities and objectives that should be obtained by particular methodologies and procedures. Value engineering (VE) techniques study the cost and added value of each part of a system and compare added values with required costs. Subsequently, VE provides a method for reducing costs and improving value [1–4]. Function analysis (FA) techniques help us understand the reasons for using each component of a system and how objectives can be achieved by using these components. The performance of a system can be improved and the non-value-added activities can be reduced by using FA diagrams. In addition, innovative methods can help designers when contradictions are observed between required objectives.

In the early 1950s, Altshuller collected 40 principles for innovation in engineering, which is known as the theory of inventive problem solving (TRIZ) and has been developed extensively, in combination with other methods [4–8]. Most new engineering inventions are intrinsically based on these principles. A designer may use these principles even without explicitly referring to them; however, perceiving these principles can improve and help reduce the time associated with implementing inventive design ideas. Furthermore, it can assist the innovation capability of a wide range of engineers.

In this paper, an empirical framework is presented for accelerating the innovation process in engineering systems. This framework also guides inventive methods toward more effective objectives. The presented action research is based on experiments from several engineering projects [9], applying VE to improve the speed and effectiveness of the acquisition of complicated engineering systems and using FA diagrams in advanced engineering systems. FA diagrams are a valuable tool to place inventive designs on the right path and accelerate system achievement. The purpose of this research is to apply VE and FA as the frameworks for innovative ideas in antenna systems. Hence, allowing designers to stop thinking about tools and, instead, ponder purpose, which leads to better ideas and solutions. After referring to FA and VE tools, methods of applying them in antenna systems for radar or imaging applications will be discussed. These antenna systems usually involve transmitted and received electromagnetic waves.

A key method for distinguishing between transmitted and received waves in antenna systems is to use circular polarization (CP). Furthermore, circularly polarized receivers are widely spread across all radio wave applications, including radar systems, earth stations, scanners and satellite systems. CP can be obtained by using circularly polarized antenna elements [10], employing regular methods such as multi-layer probe-fed antennas [11], helical antennas [12–14], spiral antennas [15–17], and aperture-coupled microstrip antennas [18]. Another method for obtaining CP is the sequential rotation technique, which can produce CP from an array of linearly polarized antennas with unique angular and phase arrangements [19–22]. Reflection-mode linear to circular polarization converters (RMCPs) [23–25] and transmission-mode linear to circular polarization converters (TMCPs) [26–29] based on metamaterials are alternative methods to produce CP from linearly polarized antennas. In addition, a combination of waveguide polarizers and orthomode transducers (OMTs) can be used in the antenna waveguide for producing both right-handed circularly polarized (RHCP) and left-handed circularly polarized (LHCP) waves [30–32]. Moreover, septum polarizers can do the same job alone [33].

The background of VE and FA applications will be introduced in the next section. FA diagrams for the antenna systems of radar or imaging applications will be illustrated and discussed in Section 3. In addition, alternatives and potential improvements of these systems will be discussed in Section 4. VE and FA are helpful tools for understanding systems and the purposes of their components.

2. VE and FA Applications

The objectives and functionalities of engineering systems can be realized using particular methods and procedures. VE is an important technique for improving the values of an engineering system, including cost reduction, quality improvement, and time reduction. Design to value is therefore a combination of design to cost, design to quality, and design to time. In addition, value is defined as the function to cost ratio in VE. Hence, VE studies the costs and values of each component of the system and evaluates if the added values are comparable with the imposed costs. Moreover, it provides methods for reducing costs and improving values, which is still a developing area in engineering fields. For example, a three-phase evaluation model including fuzzy theory, VE and a multi-criterion method was introduced by Wang et al. [34] to find optimal strategies for product configuration change, using a genetic algorithm to select suitable combinations of part suppliers. Another example is the automotive company product development process using VE and target-costing in cost management that was suggested by Ibusuki and Kaminski [35]. In addition, Tang and Bittner [36] investigated the development of creative design solutions using VE for marine construction projects. VE was also used for a major infrastructure project to obtain an appropriate alternative in [37].

Improvement of the function–cost ratio (value–cost ratio) is usually obtained using mathematical optimization of output parameters as the functions of the inputs for components of engineering systems. However, this optimization requires time and cost information, as indicated in Figure 1. Therefore, the system designer decides how much to spend on each component for the optimization. FA diagrams can be used to perceive the reasons for using each component in a system and the methods for them. These diagrams are helpful for improving system performance and reducing non-value-added components using VE methods. On the other hand, inventive methods can be useful for designers when contradictions are observed between required objectives.

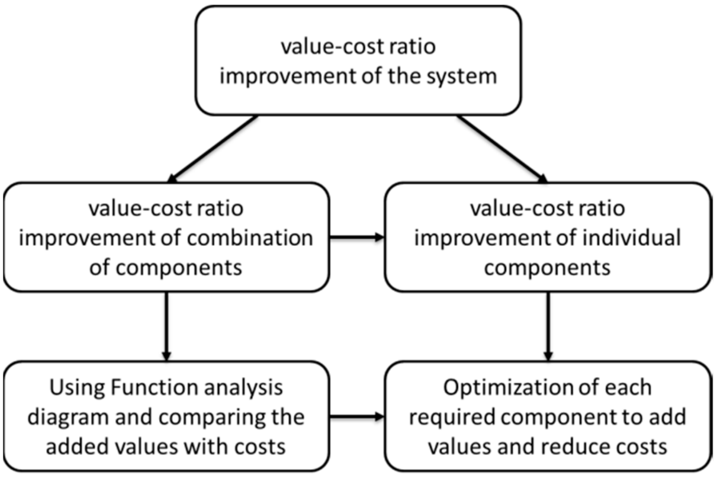

Figure 1. Diagram of the value–cost ratio improvement of a typical engineering system.

VE can result in project cost reduction, quality improvement and acquisition-time reduction, during a three-stage job plan. These three stages are pre-study (data collection), value study and post-study (improvement and presentation), which are expounded in [9] based on experiments in the automobile industry. Some ideas are also obtained using these experiments to enrich the effectiveness of VE, by means of 6Sigma workshops. A key outcome is to accelerate the overcoming of mental inertia and to find inventive methods, with an emphasis on the voice of the customer (VOC). In an engineering project, the customer can be a supplier for higher order customers. In other words, a chain of designers and customers may exist in a system, which should communicate with the VOC.

3. Antenna Systems and FA Diagrams

An important area in engineering fields, with a large number of inventive concepts, is antenna engineering, which provides electromagnetic remote links. In this section, applications of VE and FA in antenna systems, especially for imaging and radar systems, will be discussed. Moreover, FA diagrams of these systems will be presented and opportunities for functionality enhancement and cost reduction will be discussed.

For long-distance remote communication, high-gain antennas are required, which usually involve large reflectors or arrays. A typical schematic of reflectors or space-fed arrays is illustrated in Figure 2. This is, in fact, applicable for a one-way communication transmitter or receiver. However, for two-way communication, one can use two such antenna systems or two feeds for the system. The latter leads to phase error and the former is a more costly and bulky method. For radar and imaging applications that require two-way communication, the antennas should be circularly polarized, which can be a challenge for antenna designers. The reason for this is that a linearly polarized wave with, say, vertical polarization returns with vertical polarization from the target and cannot be separated from the transmitted wave. However, this is not so for CP and the transmitted LHCP wave returns with right-handed CP. Therefore, it can be distinguished from the transmitted wave, explicitly.

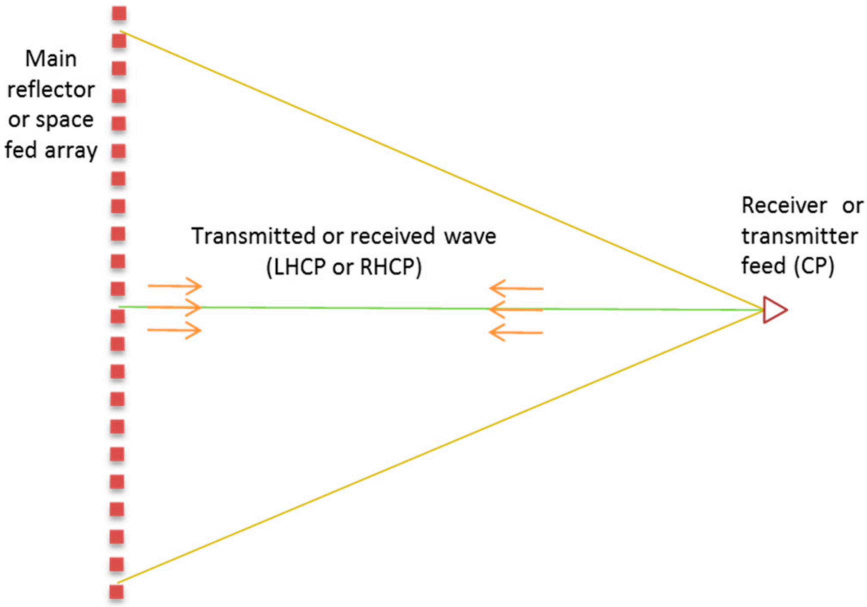

Figure 2. Schematic of reflectors or space fed arrays.

Linearly polarized feed antennas can be used for both transmitting and receiving waves, in addition to polarization converters and filters for producing CP and separating transmitted and received waves. The most common types of feed antennas are rectangular or circular horn antennas with reduced sidelobe levels to improve efficiency [38,39]. Schematics of reflectors or space fed arrays for RHCP receivers and LHCP transmitters with polarization converters and filters are indicated in Figure 3a,b, which can be used in radar or imaging systems [40–42]. Polarization conversion can be achieved using TMCP or RMCP, while the transmitting feed is horizontally polarized and the receiving feed is vertically polarized. The polarization filter consisting of horizontal wires passes the vertically polarized wave and reflects the horizontally polarized wave. The horizontally polarized wave is converted to the LHCP wave with the TMCP or RMCP, and the incident RHCP wave is converted to the vertically polarized wave with the TMCP or RMCP. Therefore, separation between the transmitted wave and received waves is obtained using a linear polarization (LP) filter, linear to circular polarization converters, and the fact that the LHCP wave usually returns with right-handed CP from its target.

Another application of CP is to receive linearly polarized incident waves with unknown polarization angles. In this example, only one receiver feed exists. Schematics of circularly polarized Cassegrain antennas are indicated in Figure 4 for receiving low-level remote signals [43,44]. The feed can be deigned initially for CP; however, linearly polarized antennas are of more convenience for designers, since they usually have wider bandwidths and simpler structures. Therefore, CP can be obtained using a TMCP or an RMCP, as indicated in Figure 4.

A FA diagram of radar or imaging antenna systems is indicated in Figure 5. It is actually an innovation accelerator diagram (IAD) that provides the reasons for each subsystem and methods of obtaining each objective. Each part can be improved, accelerated and reduced by using innovative ideas and inventive design methods. Examples of available alternatives and innovative ideas will be explained in the next section. In addition, the objectives of these systems can be enhanced by using innovative ideas.

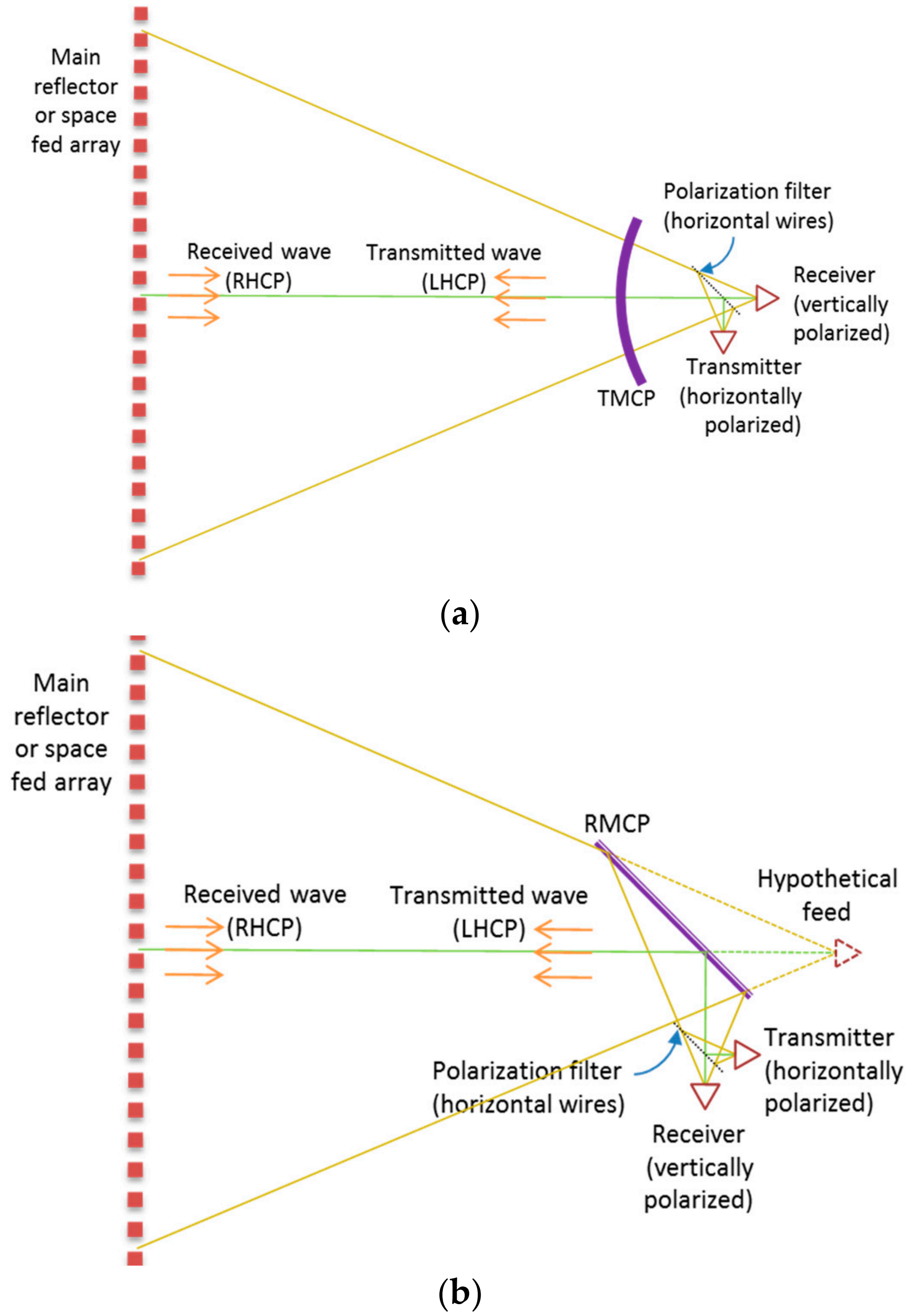

Figure 3. Schematics of reflectors, lenses or space fed arrays for right-handed circularly polarized (RHCP) receiving and left-handed circularly polarized (LHCP) transmitting waves by use of (**a**) the transmission-mode linear to circular polarization converter (TMCP) and (**b**) the reflection-mode linear to circular polarization converter (RMCP).

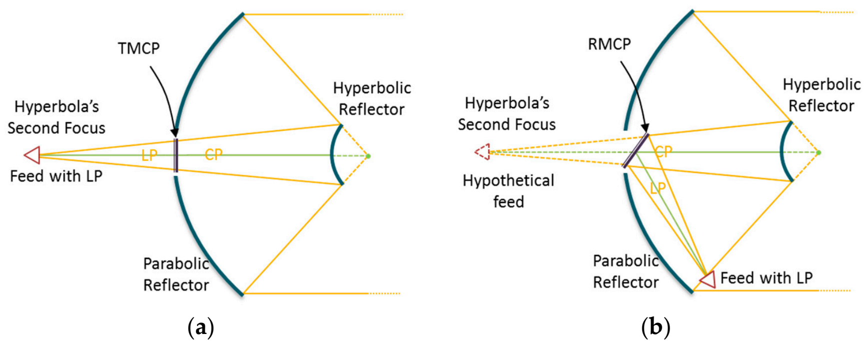

Figure 4. Schematics of Cassegrain antennas with (**a**) TMCP and (**b**) RMCP.

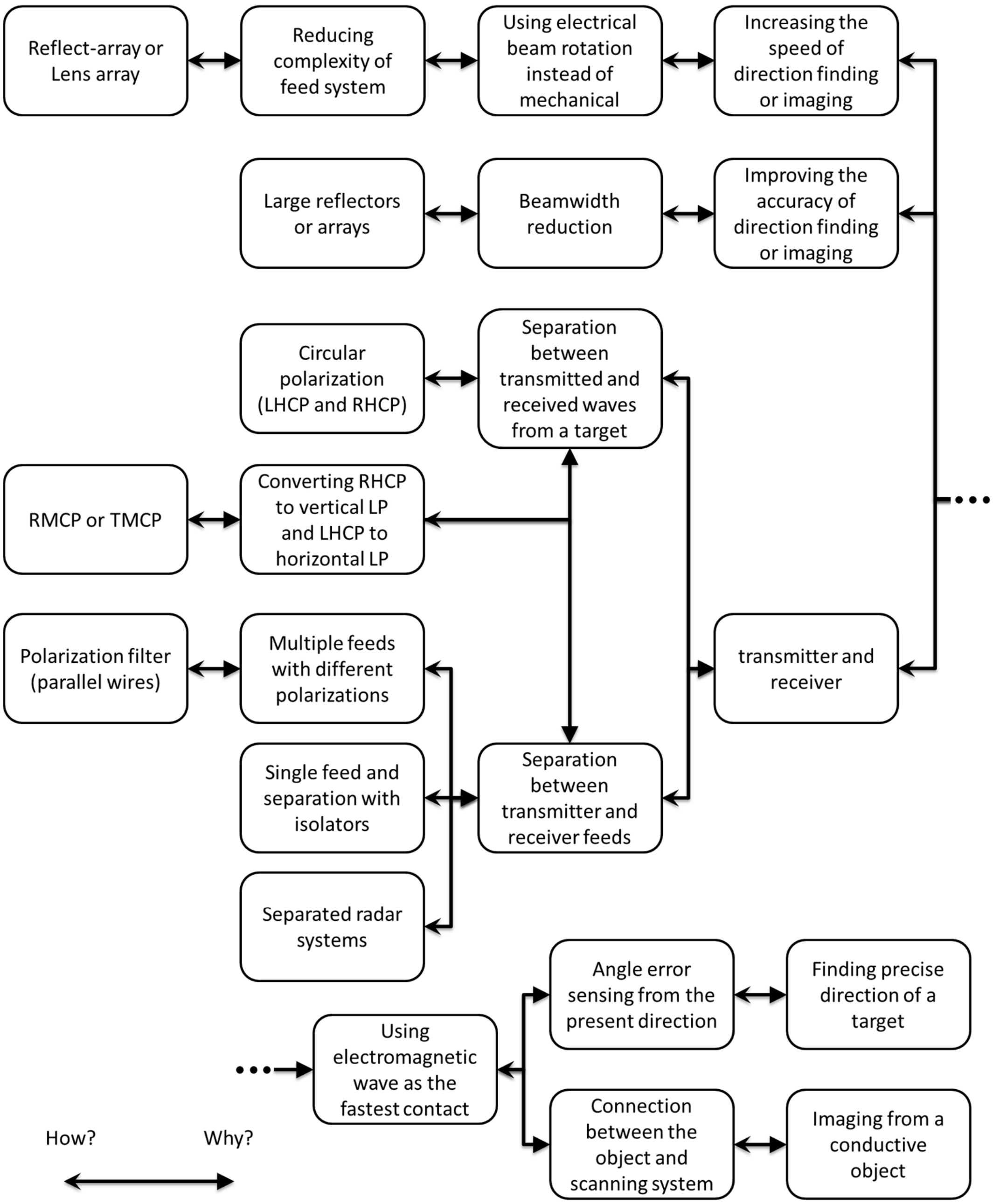

Figure 5. Function Analysis (FA) diagram for direction finding or radio-wave imaging systems.

4. Innovative Ideas for Antenna Systems

Innovative ideas are usually obtained based on a 'what if' context, in contrast with common engineering methods based on an 'if then' context [45]. This is actually obtained by 'river-jumping' and violating limitations of the previously introduced methods in a controlled manner. Innovative ideas and their outcomes will be discussed in this section for antenna systems.

In the beginning, options for circularly polarized Cassegrain antennas were studied, as indicated in Figure 3, for receiving low-level remote signals. As explained previously, the use of TMCP and RMCP instead of circularly polarized antennas is the first option. Secondly, the polarization angle of the feeding antenna can be situated in any direction; however, feasible angles are 0°, 45° and 90°. For each angle, some issues should be considered. These issues will be explained here for the RMCP and should be considered for the TMCP, similarly. For the polarization angles, 0° and 90°, the RMCP should be oriented in a 45° direction. On the other hand, for a 45° polarization angle, the RMCP can be oriented in 0° or 90° directions; however, if the system has trackers, such as the monopulse system [21,46], correct directions should be considered for angle errors. For example, if the total feed is rotated 45°, as indicated in Figure 6a, elevation and azimuth angles are not really elevation and azimuth angles, and they should be considered with a 45° rotation. However, if the antenna elements are rotated 45°, then elevation and azimuth angles are at correct angles, as indicated in Figure 6b.

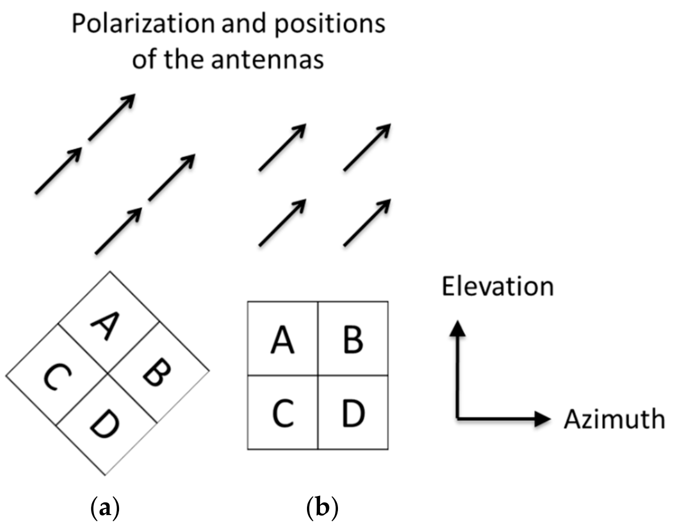

Figure 6. Monopulse antenna directions when (**a**) the total feed is rotated 45° and (**b**) the antenna elements are rotated 45°.

The next alternative in this system is the type of parabolic reflector and hyperbolic sub-reflector. These can be replaced by planar reflectors with artificial parabolic and hyperbolic phase distributions. However, main reflectors are too large and replacements may be infeasible, while sub-reflectors can be replaced, explicitly. Another choice is the total arrangement of the system, which can be changed to an offset Cassegrain antenna or other structures [47,48]. Furthermore, additional applications can be added to the system, such as dual-band operation by replacing the sub-reflector with polarization filters and using two antennas with perpendicular polarization angles, as was in Figure 3.

In addition, many degrees of freedom exist in the antenna system in Figure 4. The first is the choice of using TMCP or RMCP as the polarizer. Secondly, if a space fed array is used instead of a reflector, the transmission-mode space fed array (lens array) can be replaced by the reflection-mode space fed array (reflect-array) [26]. Another option is to use multiple reflectors instead of one reflector; the Cassegrain antenna has been explained briefly as an example of this. Moreover, the polarization of the transmitting antenna and the receiving antenna can be substituted and consequently their positions should be replaced, otherwise the polarization filter should be changed from horizontal wires to vertical wires. Furthermore, the feeds can be oriented with arbitrary polarizations, only the polarization difference should be 90°. However, the polarization filter should be at the same angle, with the polarization of the transmitter. In addition, the components of these systems often have multiple choices initially. As an example, an improvement for RMCPs can be found in [49].

Furthermore, for dual-band operation, separated feeds can be used by employing frequency selective surfaces (FSSs) to provide reflection in one frequency range and transmission in another frequency range [50]. Moreover, another type of FSS can be used for two array systems with a single feed antenna, as indicated in Figure 7. This type of FSS reflects half of the linearly polarized wave and transmits the other half with CP [51]. Other examples of this are dual-band RMCPs, which can be used to combine two separated systems with two different operating frequencies [44,49].

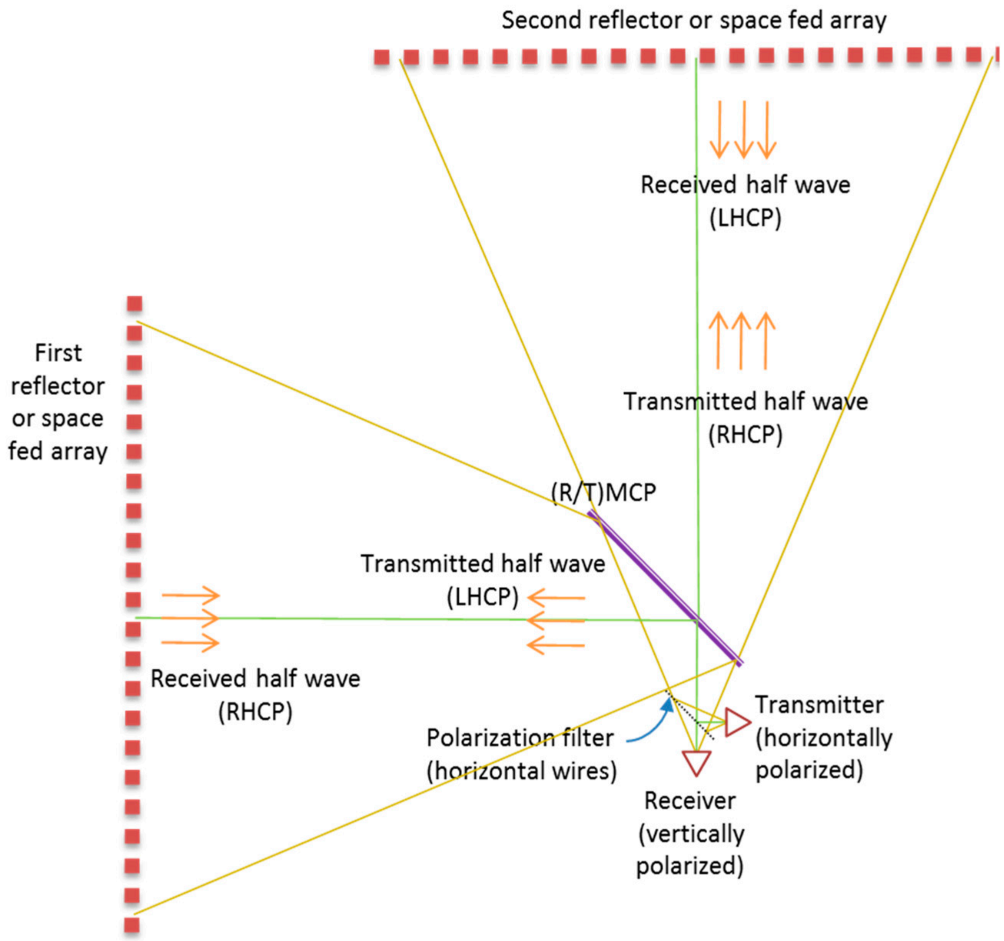

Figure 7. Schematic of the potential application of surfaces that reflect half of the linearly polarized wave and transmit the other half with circular polarization (CP) for two array systems with a single feed antenna.

The two antennas and the LP filter in Figure 3 can be replaced by OMTs and a single antenna [30,52]. It can produce both vertical and horizontal polarizations by employing an antenna, as indicated in Figure 8. This is obtained by the orthogonal connection of waveguides to a square or circular waveguide and then to the antenna. This provides good isolation between the receiver and transmitter; however, small deviations in polarization angles can reduce the isolation significantly.

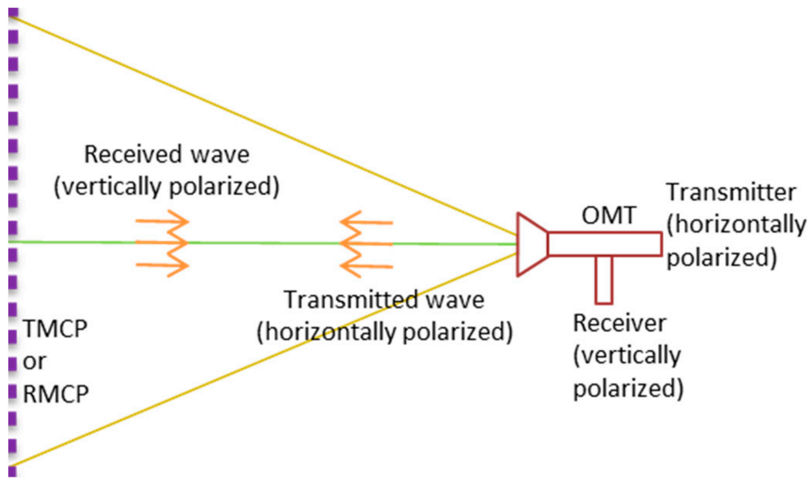

Figure 8. Feed systems using orthomode transducers (OMTs) instead of linear polarization (LP) filters for producing both vertical and horizontal polarizations from an antenna.

On the other hand, CP can be obtained using the circularly polarized antenna elements using regular methods or the sequential rotation technique, which can produce CP from an array of linearly polarized antennas with unique angular and phase arrangements. Metamaterial-based RMCPs and TMCPs are alternative methods to produce CP from linearly polarized antennas, as indicated in Figure 3. In addition, a waveguide circular polarizer can be used after the OMT with a 45° rotation to convert the horizontally polarized wave in the waveguide to LHCP and the vertically polarized wave to RHCP [31,32], as indicated in Figure 9. The waveguide polarizer usually causes mismatching and therefore reduces the isolation.

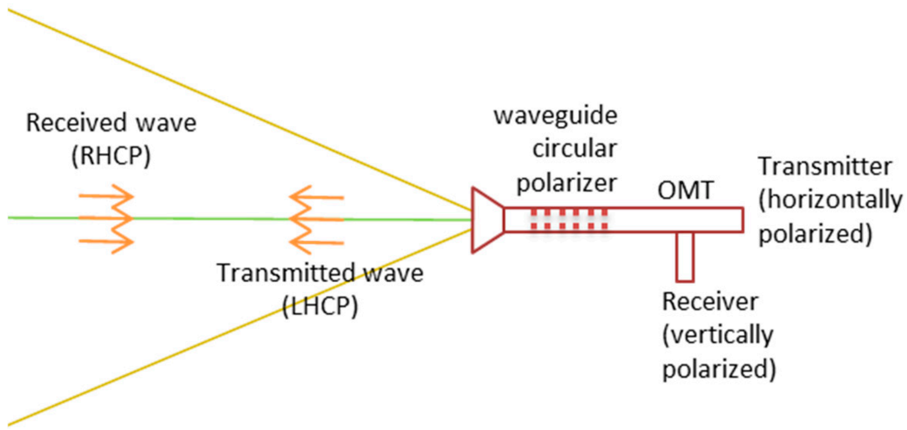

Figure 9. Feed systems using waveguide circular polarizers and OMTs instead of LP filters and TMCPs or RMCPs.

Septum polarizers are the best choice for circularly polarized antenna systems with a single feed for receiving and transmitting waves, as indicated in Figure 10. It can be observed that the outgoing linearly polarized wave is converted directly to a LHCP wave from one port and to a RHCP wave from the other [33,53]. However, the bandwidth of septum polarizers is fundamentally limited. In addition, using an antenna for both receiving and transmitting waves leads to system limitations, such as the use of trackers and multiband operations.

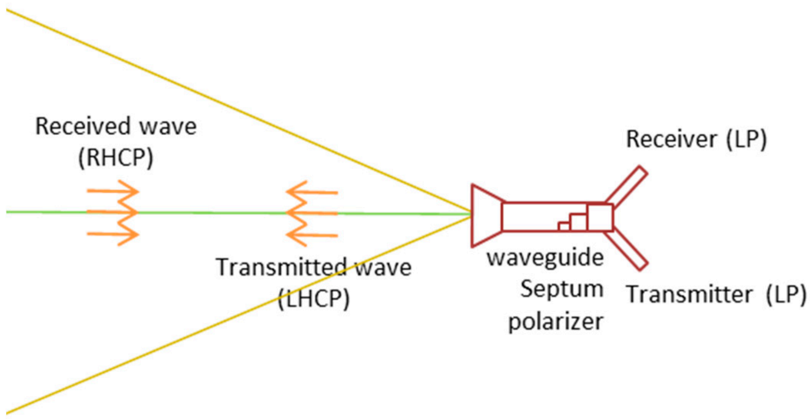

Figure 10. Feed systems using septum polarizers for converting outgoing linearly polarized waves from one port to a LHCP wave and from the other to a RHCP wave.

The use of polarization converters in antenna systems for radar and imaging purposes has some advantages over previous methods. The first advantage of this method is that the complexity of the antenna system does not have any effect on polarization. For example, for a circularly polarized antenna system with long feed-lines, the radiation of the feed-lines may destroy the CP; however, the linearly polarized antenna system may receive fewer effects from the feed-lines. In addition, the cross-polarity of a linearly polarized antenna can be omitted using a polarization filter, which is a simple wire gird. Another advantage is that the bandwidths of RMCPs and linearly polarized antennas are usually higher than the bandwidths of directional circularly polarized antennas. Therefore, the bandwidth of the total antenna system can be improved using RMCPs. Furthermore, an RMCP can be used for multiple antennas with different frequencies and directions. RMCPs can provide separation between transmitted and received waves in radar or imaging systems by converting the wave with vertical polarization to RHCP and the wave with horizontal polarization to a LHCP wave.

In both of the described systems (Figures 1 and 2) and many other electromagnetic systems, the main limitation of the bandwidth is on the 3 dB axial ratio (AR). In addition, the AR is the main limitation for multiband operation. This is actually associated with the system designer, who is the customer for the designers of each part of the system. Thus, by hearing the VOC, it can be concluded that wideband or multiband linear to circular polarization converters can improve the performance of these systems, significantly. In addition, RMCPs or TMCPs can be used as a 'common platform' for electromagnetic systems, such as those previously described [54,55].

A summary of the demanded functionalities from the described components, their advantages and their limitations are expressed in Table 1. Additionally, there are some limitations that appear with the combinations of components, as indicated in Figure 1. For example, the RMCP reflects the incoming wave in other directions than the propagation angle of the incident wave and, therefore, it has only a small effect on the reflection coefficients of the feed antennas and even the isolations. The TMCP should transmit the wave completely; however, a small reflection returns exactly in the direction of the incident wave and reduces performance significantly. Similar effects occur for the waveguide linear to the circular polarizers when situated after the OMTs. Another example is the effect of the dimensions of the feeding system on the blockage loss for the reflector antennas. This is all while there is no blockage loss for lens antennas or slanted reflector antennas.

Table 1. Required functionalities from the components, their advantages and limitations.

	Functionality Available from Components	Component	Advantages	Limitations
1	Propagating electromagnetic waves	Antennas with LP	Easy to design, high performance (bandwidth, gain, efficiency, etc.)	Cannot be used as the transmitter and receiver simultaneously, only receives incoming waves with similar polarizations
		Circularly polarized antennas	Receives incoming waves with all direction of linear polarizations	Cannot be used as the transmitter and receiver simultaneously, complicated design, limited performance (bandwidth, gain, efficiency, etc.)
2	Converting linearly polarized waves to CP and vice versa (converting, for example, vertically polarized waves to RHCP and horizontally polarized waves to LHCP)	Metamaterial-based TMCPs	Situated at right angle to the propagation angle of the incident wave, additional functionalities can be obtained	Limited performance (bandwidth, transmission loss, etc.), increased reflections for the antennas, bulky, requires standings
		Metamaterial-based RMCPs	High performance (bandwidth, transmission loss, etc.), reduced reflections in the direction of incoming waves, additional functionalities can be obtained	Tilting required, bulky, requires standings
		Waveguide linear to circular polarizers	Reduced dimensions, can be integrated with the antenna	High sensitivity, limited bandwidth, difficult for additional functionalities of the feed such as trackers, etc.
3	Separating the cross-polarity of the waves with LP	LP filters	Simple structure, wideband, low cost	Bulky, requires standings
		OMTs	Reduced dimensions, can be integrated with the antenna	Encountered difficulties for additional functionalities of the feed such as trackers, etc.
4	2 and 3 (converting first input to RHCP wave and the second one to LHCP and vice versa, directly)	Septum circular polarizers	Very reduced dimensions, can be integrated with the antenna	High sensitivity, limited bandwidth, difficult for additional functionalities of the feed such as trackers, etc.
5	Increasing gain and reducing the beamwidth	Reflectors with physical shapes	Reduced costs (usually), easily understandable structure	Required physical movement for changing the beam direction, difficult for additional functionalities
		Lens with physical shapes	Easily understandable structure, no blockage loss	Weighty, costly, requires physical movement for changing the beam direction, difficult for additional functionalities
		Reflect arrays	Weight can be reduced, can be used for electrically controlling the wave (without physical movements)	Advanced expertise is required for design, usually used for passive arrays
		Lens arrays	Weight can be reduced, can be used for electrically controlling the wave (without physical movements), no blockage loss	Advanced expertise is required for design

5. Conclusions

In this paper, we showed that VE, supported by FA diagrams, can aid understanding of the value of each part of a system, reduce total costs, and guide designers toward more innovative ideas and improvements in system performance. After introducing the background of VE and FA applications, a sketch of how to use VE, FA diagrams and functionality tables as the frameworks for inventive methods in antenna engineering was explained. FA diagrams of radar and imaging systems were illustrated as a case study and the reasons and methods for each component were discussed. A summary of the required functionalities of the components of these antenna systems, and their advantages and limitations were presented. In addition, it was indicated that some advantages and limitations appeared in combination with the components. In particular, methods for producing CP for antenna systems were studied to provide simultaneous receiving and transmitting waves. Examples of these methods were RMCPs and TMCPs based on metamaterials, and combinations of waveguide polarizers with OMTs and septum polarizers. The purpose of this research was to present a framework for guiding and improving innovative ideas in this field using VE and FA. These methods can provide better insight into systems and can improve the success of engineering projects, in combination with the comprehensive efforts of designers in engineering fields. Consequently, the benefits of VE and FA are (1) the clearance of existing functions, (2) prioritizing the customers, (3) finding system bottlenecks which require inventive methods, and (4) better communication between users and designers.

Author Contributions: Hamid Reza Fartookzadeh designed the study and contributed to writing the manuscript, especially the VE related parts, and acted as the corresponding author. Mahdi Fartookzadeh also contributed to the writing of the manuscript, especially the antenna engineering related parts. All authors discussed the results and contributed to the final manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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