2.2

THE IRON DOME PROJECT – DEVELOPMENT UNDER FIRE

An Interview with AA

The Iron Dome is a mobile system for intercepting short-range missiles that has been in operation since 2011 and is a critical component in Israel's defense against the rockets fired at it from the Gaza strip.

Developed by Rafael, the system has gained much media exposure for operational reasons, when it showed impressive interception capabilities in an entirely new area of operation. The system had also received praise for the ingenuity of its development, seeing as it marked a new accomplishment in the minimization of development costs and was completed in an unprecedented short span of time when compared to other systems of its type. In 2012, its developers were awarded the Israel Defense Award.

One of the main reasons for this project's success was the superb management of the project in general, and of its systems engineering in particular, by three key figures: the project manager, its chief systems engineer, and the chief systems engineer of its central development array. Among other things, this array included the development of the interceptor missile. The latter of the three, AA (who wished to remain anonymous) is the interviewee in this chapter. We spoke with him about the project as a whole and about its excellent systems engineering.

Managing and Engineering Complex Technological Systems, First Edition.
Avigdor Zonnenshain and Shuki Stauber.

2.2.1 BACKGROUND AND PREPARATIONS

Historical Background

One of the things that make the Iron Dome project unique is the fact that the system was to meet a concrete operational need, namely, the need to defend against short-range missiles. This, whereas, most weapon systems are made to meet future, rather than present needs. Consequently, the pressure and sense of urgency that most weapon systems development teams have to work under have less to do with operational reasons and more to do with the relationship between the length and cost of the development process.

In 2007, this issue had come up on the agenda of a committee of the Ministry of Defense, which defined the system's requirements and considered various acquisition and development alternatives. The list of requirements concerned all three of the major factors entailed in a project of this type: cost, schedule, and performance.

The pricing requirement stemmed mostly from the need for an interceptor missile, the cost of which is relatively low. This economical consideration is especially important when the system is expected to launch a great number of such missiles against a correspondingly great number of rockets, sometimes in large barrages. The price of an interceptor is measured in proportion to the damage risked with no interception system in place, including injuries and loss of human lives.

The demand for a fast-paced development was, as aforementioned, brought on by the need to provide a solution to an existing problem. The required performance standard was beyond anything achievable by existing systems.

AA specifies: "Tests were held in order to check whether existing systems or any components thereof could be of use in the new project. One type of system considered for this purpose was aircraft interception systems. An in-depth analysis showed performance gaps in the interception accuracy parameter and in the ability to destroy the target completely. Additionally, the price of such systems by far exceeded the limits posed by the requirements."

Another example was the Spyder anti-aircraft missile system. An aircraft is a much larger target than a rocket. Its successful interception, therefore, requires a system with very different specifications. Firstly, the missile can be less accurate and still effective, even if it misses the exact target by a few meters. Second, a warhead meant to destroy an aircraft is nothing like one meant to intercept a rocket – the two have different accuracy and lethality rates.

A third air defense system considered for use was the Vulcan. Mounted on battleships, the Vulcan is a rapid fire cannon that shoots thousands of bullets per minute. The Vulcan was found to have a number of limitations as far as our needs were concerned: firstly, the system was not lethal enough; second, its interception range was too short (only 1–2 km), which meant many interceptions occurring above the area the system was meant to protect. In addition, the single system's small coverage area would require a large number of systems to be deployed in a relatively small area.

The Ministry of Defense considered other alternatives, including the acquisition of existing systems from overseas and the use of other interception technologies, such as lasers, but none of them were found to provide adequate solutions, and the Ministry chose the option of local development. Several companies applied for the job, and Rafael's offer was accepted.

AA believes the Ministry of Defense selected Rafael as the contractor, among other reasons, because its offer had two main advantages over those of the competitors. The first was that Rafael was willing to work for a fixed price (for an explanation on the fixed price strategy, see chapter on the Lavi Project) at the risk of losing money. After all, there was no guarantee that the system requirements could be fully met within the limits of the agreed upon budget. Second, Rafael had successfully convinced the Ministry that it possessed the best potential for producing a solution that would be guaranteed not only to hit the targets, but also to eliminate them completely; and this, in a very short time.

AA: "The challenges were not only in developing the interceptor missile, but also in developing the ground based system itself. This system had to be able to quickly detect the threats – which had very short life spans that ranged from several dozen to only a few seconds. Within this timeframe, the system then had to identify the target and decide what to do, namely, determine whether the target posed a threat to the defended area, and if so, calculate an interception plan and execute it by firing a missile at the target. All this, while taking into account the time it took for the interceptor to reach the target, and the need to intercept the rocket at a safe distance from its designated impact area. This set of demands created a very difficult timeline problem. These dilemmas had been raised even before the project was underway, and were, subsequently, fully resolved later on."

AA finds that the risk of losing money, which stemmed from Rafael's willingness to work for a fixed price, had come with a major advantage, which later proved instrumental in the project's success: freedom of action.

Explanation: even today, when ordering projects at a fixed price is common practice (unlike before, when the prevalent pricing strategy for the development of defense projects was cost-plus), there are still quite a few defense projects priced using a combination of both fixed-cost and cost-plus strategies. This is because in many cases, the risk level is so high that even the buyer accepts that the developing company cannot afford to take it all on itself. Naturally, in these projects, the client's representatives, fearing an uncontrolled increase in expenses, wish to maintain a certain level of involvement throughout the project. In the case of the Iron Dome, however, the bulk of the risk was borne by Rafael, and so its managers had a free hand, which allowed them to employ unorthodox methods to achieve the desired results, both in terms of the quality and number of employees recruited for the project and in terms of the quality and efficiency of the managerial and technical decision-making processes. (Note that this does not mean that the client's representatives were completely out of the picture. In fact, quite the opposite; it does, however, mean that their presence was a supporting, rather than a controlling, supervising factor. For more on this, see next.)

Preparations

The first step of preparations was to determine the structure of the project's management. It was decided that the Iron Dome would be headed by the Air-to-Air Directorate. In the early 2000s, this directorate had recognized the business potential of short- and medium-range air defense systems, and so, resources were invested in the evolving area of air defense. This investment also came in the form of making adjustments in air-to-air missiles, an area in which the directorate acquired considerable knowledge and many years of experience (the aforementioned Spyder System was the result of one such development).

The Setup and the Selection of Project Managers

The next step was determining the organizational structure of the project's advance setup framework. A preliminary distinction was made between the central development array, which included the interceptors, the launchers, and the casings (most of the development efforts were invested in the interceptor), and the remaining components of the ground-based system, which included the radar, communications, and control units. Beside the head of the program who focused on the broad management of the project stood two of the very best professionals in Rafael: H, the head of the interceptor, launcher, and casings development array; and D, the chief systems engineer for the entire program (shortly after work on the project had begun, our interviewee, AA, joined these two as the chief systems engineer of the interceptor, launcher, and casings array).

It should be noted that although the Iron Dome was developed as part of the Air-to-Air Directorate, the people who led the program came from various organizational units throughout Rafael.

During the project's early stages, it was perceived as one that did not require high technical capabilities, compared to Rafael's other flagship projects. A missile meant to counter aircrafts and ballistic rockets is nothing like a mere rocket interceptor. In other words, it was only natural that, not seeing the project as a high-end technological challenge, the engineers at the directorate were not lining up to join it.

AA demonstrates: "When people started talking to me about joining the Iron Dome, a colleague from another project met with me and said 'come to us, ours is a serious project, cutting-edge technology.' That was the attitude towards the Iron Dome. But after a while, when the development began to pick up speed, things changed, and the people in Rafael began to see the Iron Dome's significance."

This was true for Rafael's lower ranks. The executives, on the other hand, were well aware of the professional and management-related challenges, as well as the risk they had taken upon themselves. Consequently, they wanted the very best people within their reach at the time to lead the project. So, it came about that the three professional leaders of the Iron Dome program, H, D, and AA, were brought in from outside the Air-to-Air Directorate.

The reason we chose to mention this fact is that AA sees this as a major advantage that contributed to the project's success: "H came from the systems division, and he had experience in project management. Although the projects he had headed were unrelated to missile development, he did have experience in tools that included a kind of interceptor. In retrospect, he turned out to have been an excellent choice, because he saw things differently, which allowed him to be free of the restricting influence of past approaches, other projects and people. (This principle is demonstrated later in this chapter, in the example of the choice of servo.)"

H was the first to be recruited (to head the development of the interceptor, launcher, and casings, as aforesaid). He then recruited the next key position holder, the chief system engineer for the entire program, D, who had come from the missiles division where, in the years before the Iron Dome, he had mostly dealt with air-to-surface systems. AA describes D as a systems engineer of extraordinary talent.

We asked him to elaborate on what made D such a great systems engineer.

AA: "The ability to completely separate his professional agenda from his ego; although he has exceptional professional capabilities, he never becomes entrenched in prejudice. As a systems engineer, this approach allows him to have a dialogue with a wide range of people, some of them young, some more experienced, some who think like him, others who do not; and create a dynamic that leads to the right places.

Sometimes we deal with questions we have no answers for; problems, to which we see no solution from where we stand in time (unlike formal work procedures, wherein you know that if you take a certain path, you will can expect a certain result). In these situations, it is necessary to create the process that leads to a successful solution. D is able to create a dynamic that eventually leads to results – a dynamic that combines professional and intellectual skills with an egoless ability to listen."

First Steps

H and D were preparing for action. Preliminary preparations were carried out in collaboration with AK, a talented and experienced missile expert. Together, they made several key decisions, such as placing not only performance, but also costs and scheduling on top of their priority list. This meant that every engineer who worked on the project knew that when he was deriving the requirements for the various arrays in the system, cost and schedule were no less important than performance. This decision is not to be taken lightly, even in fixed price projects, because it goes against the engineers' natural tendency to ensure perfect performance first.

AA: "As engineers, if we do not meet performance requirements, we will feel we failed; if we do not keep up with the schedule, we may feel uncomfortable; but if we go over-budget, our egos won't feel a tingle. In many projects, engineers are told that out of the trinity of schedule, performance and cost they have to pick the top two. In The Iron Dome, all three were deemed equally important. Adherence to schedule and cost requirements was strictly maintained. This approach allowed the creation of a missile that was much cheaper than others in its category, and able to meet the performance objectives without going overboard with excessive requirements."

He gives an example of a "technological" key decision made by H and D, which concerned the type of servomechanism ("servo") that controlled the missile's steering system: "We began by planning the general configuration of a missile that resembled an air-to-air missile, and then asked several fundamental questions, in order for it to meet the requirements of our project. One of these questions was which 'servo' we should use for the steering system. The 'servo' must move the missile's maneuvering fins with accuracy and finesse. We deliberated whether the 'servo' should be pneumatic (a technology based on compressed gas) or electric. The Air-to-Air Directorate had always used pneumatic servos, because their properties suited air-to-air missiles. Over the years, the developers had come to believe that if a missile needed a fast, light-weight, low-volume steering system, the 'servo' had to be pneumatic. On the other hand, the Air-to Surface Directorate made bigger missiles, which traditionally used electric servos. These are usually larger and heavier, but can be easier to realize, require less design rotations, and are easier to model and incorporate into the missile's control system. They are also easier to work with in the laboratory, during the testing phase. An electric 'servo' needs only to be plugged into a computer, and testing can begin. With a pneumatic servo, testing is more complicated. It is powered by high pressurized gas, and so testing it in a laboratory requires a special support system and careful adherence to safety protocols (it is reasonable to assume that this was another reason this decision was deemed so important: time was of the essence in the Iron Dome project, and a more complex testing process would have had an impact on the schedule – the authors)."

H and D decided on an electric 'servo'. Their choice caused what AA referred to as a "sensation," because it was considered unorthodox in the Air-to-Air Administration, where the project was being developed.

Why use such an extreme term to describe what appears to be a practical, professional decision?

AA: "Because, in a way, it ignored the vast pool of knowledge Air-to-Air had accumulated over the years; knowledge, which was of great value and relevance to our project, too. Moreover, the challenges of the Iron Dome project resembled problems the Air-to-Air Directorate had handled in the past; and there they were, offering a different solution than what had always been used. Situations like these raise questions like: 'is the new solution really a good one? And if it is, how come we have never tried it before?' This certainly was an extraordinary decision, and it demonstrates the advantage of having a project manager who comes from outside the directorate, and does not feel bound by its past decisions."

However, AA stresses that the directorate heads examined the decisions of The Iron Dome managers on the merits and did not let other considerations, insofar as they arose, affect their judgment. The eventual result of this unique design process was a simple electric servo that met the cost, volume, weight, and performance requirements.

The next phase was forming a preliminary setup team. This was when AA, a relatively young electronics engineer, who had begun working for Rafael in the year 2000, was approached about joining the Iron Dome project.

AA: "At the time, I was a development team leader at the Engineering and R&D Administration. My work focused on missiles and control. D and I had met when we worked on an air-to-surface system together. When the Iron Dome directorate was beginning to take shape, I was leading an algorithm group in the Air-to-Surface Directorate and D would consult with me from time to time, as he worked on the preliminary concept. Seeing as the project I had been working on was nearing its completion, he offered that I join the setup team as an engineer. Incidentally, two days before D approached me with the offer to join the project, I had seen the rockets fired at Sderot on the weekend's newscast, said 'it cannot go on this way,' and decided that come Sunday, I would go and see how I could contribute to the war effort. That Sunday was the day I met D and got the offer to join the project as an interception engineer."

By then, a small group had already been recruited for the project. Among its members were a software engineer, an electronics engineer, a structure engineer, and an integration engineer. This was the team that created the system's preliminary design.

AA: "At that point, we mostly focused on the interceptor missile because that part of the project entailed most of the risks, and they had to be addressed as early-on as possible in order for the project to keep up with the schedule. Additionally, it was important to present the risks we had mapped as soon as possible, and show that some of them could be eliminated as early as during the laboratory testing phase, in partial system trials. At the same time, we had to derive requirements and develop arrays."

Several months later, the first test called a "Configuration Test" (CNT – Configuration and Navigation Test) was held to assess some of the project's risks. In the early stages of the project, the goal was to launch a missile that resembled the final product as much as possible, as soon as possible. This could be done because quite a few parts and arrays (such as the "servo" prototype described earlier) were already in existence and had only to be incorporated into the system with various adjustments. So, a preliminary prototype was made and launched in order to test the concept. Then, based on the test results, we could verify and remap the risks with better accuracy, identify new risks, and discover which risks did not call for as much concern as we had thought. These results created a new foundation for continued development.

After the CNT, AA became the chief systems engineer of the interceptor, launcher, and casings development array, despite having no experience as a systems engineer. He had, however, had "some experience with systems," as he puts it: "I had led a fairly large group of people. That kind a job always has some systemic aspects. What's more, the unit I worked in, the missile and control group, was a systemic group by definition, engaged in performance, algorithms, software, aerodynamics, testing, and test planning. A considerable part of Rafael's systems engineers rise from among the members of that group."

The number of people who worked on the project grew steadily, even in the supporting administration.

AA: "In the R&D and engineering administration, groups were forming, specializing in missiles and control, navigation, aerodynamics, mechanics, electronics and integration, equipping, thrust, warheads and software."

Under D's leadership, there also began a rapid development of the ground battery array, including the radar, communications, and the command and control car.

2.2.2 THE MANAGEMENT OF THE PROJECT

An analysis of AA's words leads us to the conclusion that the Iron Dome's success stemmed from, among other things, a combination of three key components: the project's organizational structure, the atmosphere among the work teams, and the work patterns. These components embodied the project's "lateral" systems engineering, a combination of technology and people management; according to AA: "Systems engineering is the central pivot that coordinates and times performance."

Lateral Systems Engineering

The nature of systems engineers is to make connections between subsystems. The more connections there are, the more complex the system and the higher the risk of malfunctions. It is, therefore, logical to aspire to minimize the number of connections in order to simplify the system (in this case, the organizational system). Accordingly, the philosophy behind the management of the Iron Dome was what AA refers to as "small systems engineering." He mostly refers to the lateral activity, which was managed by only three people throughout the entire project, even when it employed hundreds of engineers.

AA: "Compact systems engineering causes all the knowledge to be accessible all the time. We did have systems engineers for each field, like software, electronics or mechanics; but the entirety of the technological activity was managed by only two people: D and myself (this suggests that D and AA were interdisciplinary systems engineers. The other systems engineers in the project worked within the discipline they had specialized in – the authors). Our work connections ensured that there was not one detail in the whole project that we were unable to figure out either between the two of us, or by consulting one or two of the experts in the relevant field. So when a problem in a certain area needed resolving, we only needed a total of three or four people to be present at the discussion. This allowed us to find solutions more quickly."

There are more than a few projects where the equivalent team numbers 10 or more systems engineers. Why use such large teams, if they are so obviously less effective?

AA: "There are a few reasons for this. One of the more important factors this depends on is the people selected to lead the project. If the project is led by people who are able to address a wide range of issues and maintain a good, balanced relationship that allows the project's lateral activities to proceed smoothly, a small group of managers can suffice. A good choice of systems engineers in the early stages of the project is what makes small systems engineering possible."

Sometimes, the increase in the number of systems engineers working on the project happens further down the road. The project starts off with a small group of systems engineers, which grows as the project progresses.

AA: “I have seen cases where people suddenly see a need that another systems engineer could meet, and then appoint someone to run that whole discipline; then, they discover another need and find someone else and so on. At first glance, this seems like the right things to do; everyone takes care of their own area. But the problem is that in time, you lose the ability to take in the entire picture with one glance. And then you have to have a discussion with 10 other people to find the root of a problem.”

The Atmosphere Among the Work Teams

One of the reasons for the project’s success was, in AA’s opinion, the pleasant atmosphere that prevailed in it, which created an open, egoless social environment. Very experienced people worked alongside young people who brought in fresh, different perspectives. There was no “cast system” of senior and junior employees; rather, there was a synergetic, harmonious air of practicality.

Another factor that characterized the way the Iron Dome was run was the unwavering commitment of the people to its success. There were a number of reasons for this commitment: the main reason was, of course, the sense of urgency.

AA: “The people in other Rafael projects also showed commitment to the success of their missions, and some of those projects may even have been more important for Israel, but here we had an immediate problem that needed to be resolved. In the past, I had been involved in important projects that worked on responses to future threats; but in The Iron Dome, we were working on a problem we were experiencing every day. We saw the people being fired at on television and understood the urgency. We were given a chance to solve a very serious problem in a very short time-span. This was how the Iron Dome people talked. They identified with the goal and were committed to the mission.”

On this matter, he adds: “The client’s demand for a tight schedule was no less important than the operational requirements. This was not a common situation. Although there are other projects where scheduling is important, the stated reasons for this are usually that ‘it’s a milestone’ and that ‘the division made a commitment before the client.’ While these reasons are certainly valid, they are not enough to create the level of commitment we saw in The Iron Dome. The gruesome reality greatly contributed to the people’s commitment to keep up with the schedule.”

Another reason we have already mentioned in the discussion about the choice of project managers was the business risk.

AA: “The management of the company and the heads of the division (Rafael’s missile division, the organizational body in charge of the Air-to-Air Directorate – the authors) understood that if they did not fulfill their obligations, there would be considerable losses. Rafael had taken a great risk, and this meant that the key positions in the project had to me manned by people who were very good at their jobs.”

It follows that the quality of the people, both as professionals and as human beings, was instrumental in the project’s success and the atmosphere that prevailed in it.

AA expands on the aspect of professional ability: “For a project to succeed, ‘stars’ need to be placed in key positions, critical junctions throughout the project. These are usually the development team leaders; they are the ones who provide solutions to complex problems. It is a matter of making the right strategic, organizational decisions, placing the best people in a project, the success of which is important. Throughout the duration of the project, when we needed someone to help us with a certain problem, Rafael assigned us the very best people at its disposal.”

The Work Patterns

The systemic structure of the Iron Dome project, its management methods, and work atmosphere led to the formation of work patterns based on a principle of continuous improvement, up to the point where the result met the requirements.

AA demonstrates: “Once the price of the interceptor had been determined, a design-to-cost process began. This meant that the price became a top-priority requirement in the development of each array. This kind of process needs to be the approach from day one, because decreasing costs retroactively is nigh? impossible. We divided the interceptor into several arrays and estimated the relative cost of each one. The assessment was done in comparison to other missiles. For example, let’s assume that the steering system costs 10% of the value of the missile. If the missile is considerably cheaper than other missiles, then the price of the ‘servo’ is extraordinarily low. Additionally, H (the head of the main development array – the authors) determined that the ‘servo’ should have no more than ten components. People argued that that was an impossible requirement, because it was a complex mechanism, but H persisted, saying ‘for this price – no more than ten components.’ Then, the engineer who led the ‘servo’ development group came to H’s office and said: ‘I have a preliminary design.’ H asked him: ‘Did you meet the cost requirement? How many components do you have?’ the leader answered: ‘twenty one components, still not sure on the price.’ H said: ‘come back when you get to the required price and manage to have ten components.’ The leader insisted: ‘But I’m already here, come see what we’ve done.’ H: ‘Not until you have ten components.’ A few weeks later, the leader came back with a servo that met the price requirement and had only ten components.

Later, I got a chance to talk about this with the head of the department that developed the servomechanisms for Rafael. He told me: ‘this servo is something I have wanted to make all my life. It’s so simple and works so well; it is easy to assemble and also very cheap.’

We could have gotten a more complex ‘servo’ in one development rotation. But creating a ‘servo’ that simple required more thought and more talent. Finding a complicated solution is fairly easy. To find a simple solution, one had to start thinking. This example demonstrates the method used to develop other parts of the Iron Dome as well. It shows the tremendous effort invested in making each and every array as simple as it could be.”

This example also shows how a lean budget can send a team in search of better solutions.

Does this mean that the products of a tightly budgeted project are superior to those of a well-funded one?

AA: "Only when the people working on it are very good; especially the leaders and members of the development groups. In my opinion, they are more important to have around than talented managers. In many cases, when a project manages to overcome a particularly difficult hurdle, the solution is not found through the use of management manipulations, but by brilliant minds; at times, it is discovered by one man who figures out how to solve the problem. Sometimes you look at the team and realize that without each and every one of those people, the project would have been stuck."

Working with the Client's Representatives

We have already mentioned that the Iron Dome being a fixed price project allowed its managers to give the developers a high degree of freedom. This was because the level of the involvement of the representatives of the client, the Ministry of Defense, was relatively low. But AA stresses that the relations between the client's representatives and the developers were very cooperative; among other things, because of the personalities of the people involved on both sides: "It did not feel like we were on the opposite sides of one process, a supplier and the client criticizing him; it felt like teamwork. They would come to see how they could fit into our teams and contribute. For instance, we needed certain intelligence information in order to make a decision, and they made sure we got it. We needed a space to perform a trial in a military base – they took care of it. They were another mind on the team, regardless of their professional background, because in brainstorming, what matters is common sense.

The Iron Dome is an example of a project where the client nearly merged with the supplier. This is not to be taken for granted, and some would even criticize it, because perhaps the client should keep his distance, so as to be able to represent the other side's point of view. If the client cannot do that, there is nobody left to give criticism. But in the case of the Iron Dome, it worked out great, because of the client's representatives, who maintained the independence of their thought processes."

AA admits that one cannot predict the results of such collaborations. But one cannot argue with the fact that the human composition of the Iron Dome made it work extremely well.

Working with the Users' Representatives

Another contributing factor to the project's success was the involvement of Air Force officials in the system's early development stages, mostly in matters that concerned its use. The Iron Dome people understood that they had to take into account not only the missile's accuracy and efficiency, but also the usability of the whole system. Thus, for instance, once the launcher and control car designs were complete, Air Force field personnel tested the system and practiced using it. They assessed its performance and suggested improvements.

AA: "The improvements made due to the operational experience of the Air Force personnel allowed us to make the final adjustments. These are critical for the system to be used comfortably in the field. Later on, the Air Force expressed its great satisfaction with how comfortable the system was to operate. In addition, this collaborative work pattern was instrumental in the quick introduction of the system to operational use."

Working with the Production Array Representatives

In many projects, the production process does not begin until the development process is complete. At first glance, this appears to be reasonable, because in the early stages of the project, developers focus on finding ways to meet the system's operational requirements. However, sometimes there are constraints that arise as a result of the limitations of the production process. In these cases, many developers say that they would not be able to divert their attention to the requirements and challenges of production until the main development risks were eliminated and leave the production specialists to their own devices. Of course, this approach lengthens the time it takes to complete the project.

When asked why, then, are the production people not included in the early development stages so that they can help prevent some of the problems production has to handle later on and save time, AA responds: "This requires resources and attention that the developers are often short on. Think of a development engineer who has a difficult problem with a certain array. He does not know how to solve it and he invests a lot of resources into finding the answer. He goes to sleep with the problem and he wakes up with the problem. On Saturday, instead of playing with his kids in the swimming pool, he thinks about whether it should be solved this way or that way. Then suddenly, someone from Production shows up and says: 'three or four years from now, when we start manufacturing the system, I'm going to want to add a few more minor requirements.' So, although taking production constraints into account sounds like the right thing to do in hindsight; in real time, it is anything but that. Additionally, in certain cases, discrepancies are formed between certain production requirements and the existing design, and additional thought is needed to settle them."

"Production and development are two very different worlds," says AA. "Each of them has its own thought patterns and its own priorities."

Not so for the Iron Dome. Here, too, the project managers chose an unorthodox approach. The pressing schedule pushed them to include people from Production early on, during the advance development stage. Moreover, the production process itself had begun before the final testing phase was over. This decision may have been risky, but the involvement of Production in the development stages minimized the risk levels.

AA shows how working together with Production had contributed to the success of the project, by helping the project meet one of its most crucial requirements – to keep up with the schedule and make the system operational as quickly as possible (some of the details in some of these examples have been purposefully changed for confidentiality reasons – the authors): "Suppose that Production deems it important to divide the missile into modular units. The developers, on the other hand, might find it more convenient to put the whole missile into one sleeve and leave the Production people to figure out how to handle it. This was not the way things were done at the Iron Dome, where the insights of Production carried a lot of weight. We discovered that with a little effort early on, during the design stages, we could achieve a tremendous advantage later, during production.

A good example of this is the time the Iron Dome's missile arrayment (the incorporation of the various arrays into one missile) had taken to complete – roughly one hour. Considering the fact that similar missiles usually take one to two days to array, this did not only save the project considerable time, but quite a bit of money."

The Iron Dome's managers were fortunate, because the production specialists they had cooperated with were, in AA's words: "Excellent production experts and engineers, who brought unique perspectives to the project and helped us find solutions."

He demonstrates: "We designed an optical component that had parts glued to its circumference in a very specific pattern. The developers devised an 8 hour long assembly process. The process was so lengthy because once one part was glued on, it was necessary to wait until the adhesive was partly dry before proceeding to the next part. An experienced production technician said that our process took too long and suggested another way. His process took less than an hour. It was wonderful, especially for a system like the Iron Dome, where processes constantly needed to be simplified to save time and costs. Had the situation been different, they might have told us 'why are you wasting your effort on this? The developers have thought of everything and their process is correct. Please follow procedure."

AA summarizes: "Rafael had learned that the inclusion of Production in the early stages is a reasonable price to pay for the benefits it yields. Today, they are trying to implement this lesson in other projects."

Checks and Balances – Making Trade-Offs

One of the most obvious expressions of a systems engineer's work is the creation of checks and balances between interconnected systems and subsystems. In the professional jargon, these are called trade-offs. AA agrees with this statement (which appears in many of the chapters of this book) wholeheartedly. He holds that it is a systems engineer's most important mission and gives an example that illustrates how this work requires both professional knowledge and a broad, systemic perspective. These, in AA's view, are the things that make a good systems engineer: "In the early design stages, we allocate requirements to the different arrays. The assumption is that when the arrays are later put together, the requirements will be met. We also often include a safety margin, so that a deviation in a single array does not bring down the whole concept. The problems start when one of the arrays cannot perform up to par. When that happens, one option is to persist – to continue investing efforts and funds until the array meets the requirements. Driven by their egos and the desire to overcome the challenge, this is what engineers naturally tend to do.

This is where systems engineering comes in. It examines how another array can make up for the deviation; especially if that array has been completed with no hitches, meets the requirements, and can deliver even more than it currently does. If a certain array presents a difficulty, we first check whether a reasonable effort has been invested to make it meet the requirements, or whether a grievous error had taken place. Here too, it is good to ask ourselves whether we have arrived at the 'knee-point,' the point where even a slight improvement requires a lot of effort, which, of course means it is advisable to go no further. The next step is to consider how we can make up for the difficulty by improving other arrays – this is an acceptable solution in many situations."

He demonstrates by describing a specific case (some of the details of which have been changed for confidentiality reasons – the authors), when a systemic process of balancing different disciplines produced a satisfactory solution ("satisfactory, but not optimal," he stresses) for the operational system: "The Iron Dome system has a sharp, cone shaped component called a 'discard ogive,' part of the interceptor missile. When the interceptor approaches the target, the 'ogive' is discarded and the homing head is exposed. This part of the system entails a very complex development process – not only does this process have to take place while the missile is flying and even maneuvering through the air at great speed, the discarding of the 'ogive' brings about a sudden change in the missile's aerodynamic configuration and subsequently changes its behavior. Moreover, the ogive's separation and distancing from the missile must be perfectly smooth; it cannot bump against the missile, not even enough to leave a scratch. And to make matters even more complicated, the discard must be possible under various flight conditions: at low or high speeds and at various air densities (which change depending on altitude and the maneuvers the missile is performing). Of course, the 'ogive' also has to be very cheap and sturdy, and has to possess certain aerodynamic properties. These were the requirements, and the engineers had to rack their brains for the answer.

Now, when you look at the process, you see the conflicts of interests: what works in one situation does not work in another. When we began to develop the array, we soon discovered that the mission was a 'challenge,' which really is mild word for 'impossible.'

So what did we do? First of all, we mapped the problem, noting the things we could improve upon easily, and the ones we would have to struggle with. Next, we had to reexamine the requirements, in case some of them would turn out to be irrelevant. For instance, the missile would only be able to make sharp maneuvers at low altitudes, because at higher altitudes, there would not be enough air for sharp maneuvers. There was, therefore, no need for the missile to be able to perform sharp maneuvers and withstand low aerodynamic pressure at the same time. This narrowed our range of requirements down to the relevant situations and sets of requirements. If the team is still unable to meet the requirements at this point, it moves on to the next step.

Another example: we had a conflict of interests between the strength of the 'ogive,' which we achieved by adding layers and making it thicker, and the aerodynamics – which were negatively impacted by the ogive's increased sturdiness. Now we had to decide how thick we could make the 'ogive,' so that it could withstand both the extreme conditions of its discard and the impact to its aerodynamic structure, these being only 2–3% of the cases.

We made a tradeoff between strength, aerodynamics, and mechanics (the discarding mechanism); and to that we added the algorithms that had to make up for the gap we had been unable to bridge (so that the missile could still withstand extreme conditions). And so, we arrived at the 'knee-point' – the point where any further improvement would bring only negligible benefits. From there on out, it was no longer worthwhile to invest in this area."

On Models, Simulations and Testing

The more complex the system, the less one can safely rely on human intuition to make it work. Complex systems need to be periodically examined from the earliest stages of their development, in order to locate limitations and failings that advanced planning had failed to foresee. This is why the system simulation exists – to test the design, consider alternatives, plan tests, research performance and check various algorithms.

AA: "The quality of the simulation is measured by two main criteria: how close the simulation is to real world physics, and whether the simulation includes most of the subsystems that make up the main system. Making a good simulation is an art-form. Is entails the creation of a flexible, modular structure, able to handle numerous components that change throughout the development process. The structure of a simulation must allow it to test a system that grows continuously, as more and more new components are added, and as existing components are enhanced."

This suggests that the construction of a simulation also requires trade-offs: "You have to decide which phenomena or components to model, and how accurate and detailed that model should be. If the model is very detailed, you can simulate more phenomena and get closer to reality; but high levels of detail cost precious time and money. So it is important to use common sense when deciding what level of detail should be considered adequate. A simulation only has to include the most influential, most important phenomena. The development of the simulation is a continuous process that relies on learning from tests or field activities."

Evidently, the Iron Dome had set a high bar here, as well. The project used systemic models and simulations extensively. The prevalent opinion in Rafael is that this element was vital to the successful development of the system in such a short time and its rapid entry into operational use.

A similar approach was adopted in the planning and operation of the testing array: "The development process included many tests. We tried to hold a test every few months. We tested many different scenarios, some of which even lay outside the system's performance range. Our goal was to locate weaknesses and limitations and make improvements and corrections accordingly. Large numbers of tests are a contributing factor to success, but they also make the system more expensive. However, the low price of the interceptors and of the Iron Dome targets allowed for a relatively large number of tests."

To conclude, the success of the Iron Dome project – an efficient technological system developed from scratch in a remarkably short time, while remaining within the limits of a strict budget, was achieved thanks to a human conglomerate of project managers and engineers; a conglomerate that had the ingenuity to use creative systems engineering and form a challenging and highly committed work environment. Another factor that contributed to the project's success was the fact that its developers were allowed to test the system's function in "real life," seeing as the IDF had used it even before it was fully approved for operational use.